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TYPES OF SINGLE OPERATOR ARC WELDING GENERATORS

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

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TYPES OF SINGLE OPERATOR ARC WELDING GENERATORS

PART I.

ARC WELDING PRACTICE AFFECTING THE GENERATOR

1. Definition. - The process of arc welding has been defined as the utilization of the intense concentrated heat produced by the electric arc for melting and fusing the metals to be welded. The metals instead of being heated and forced together, as in forge welding, are melted at their point of contact and the two metals fuse without pressure at this point. It is usually necessary to feed extra metal into the arc, which melts and fuses with the other molten metal, thus helping to build up the joint between the two pieces. Arc welding is used not only to join two or more pieces, but also to build up a single piece. In this case, metal is fed into the arc, melts, and fuses with the part of the piece to be built up that is melted by the arc. In its processes and results arc welding is very much like casting.

2. Methods of Arc Welding. - Several different methods have been devised for the use of the heat of the electric arc for welding. The method used in a majority of cases in this country is the metallic electrode process. In this process the positive side of the welding circuit is connected to the work to be welded. The negative side is connected to a metal rod or pencil. This metallic rod, forming the negative electrode, is brought into contact with the work and quickly withdrawn a short distance. As the electrode is withdrawn an arc is formed between the work and the electrode, which melts a spot on the work and also melts the end

of the metal rod. The molten material from the rod is automatically deposited in the hottest portion of the weld surface. The metallic electrode may be bare, or it may be coated with some substance which tends to prevent oxidation of the molten metal passing thrcugh the arc. Both types of electrodes are in popular use. When the bare electrode is used, this process is sometimes called the Slavianoff process, and when the coated wire is used, it may be called the Strohmenger-Slaughter process.

For metallic electrode welding with bare electrode approximately 20 volts are required at the arc. This voltage is approximately constant for any arc current or any permissible variation of arc length. If coated electrodes are used, the voltage required is higher, usually about 35 volts. This voltage, however, depends on the coating used on the electrode. The amperage used depends primarily on the thickness of the work. Sufficient current must be used to melt a portion of the surface of the material to be welded. Due to the high heat storage capacity and to the better heat conduction from a point in heavy work, it is found that larger currents must be used for heavy work than for light. For 1/8" plate, about 75 amperes should be used. For 1" plate, about 200 amperes should be used. In metallic electrode welding, the arc should be kept as short as possible. If the arc is long, natural air drafts disturb the stationary arc and tend to move it around an extensive surface of the work. The heat is not concentrated and the surface of the work is not properly melted. Besides, with a long arc, the molten metal in the arc is very likely to become oxidized, and then when deposited in the weld, it will weaken it.

The arc gap is usually held at about 1/8" length.

Although the great majority of all electric arc welding is done by the metallic electrode process the carbon electrode process is also frequently used. In this process, the metallic electrode is replaced by a carbon electrode. After the arc is formed, a rod of metal is fed into the arc from the side by the operator. The heat of the arc melts this metal and it fuses with the molten portion of the work. Inasmuch as the carbon tends to be carried into the weld, the carbon electrode process produces a weak joint. Therefore, this process is not used where great strength is required. It can neither be used for welding on a vertical surface nor where the work is overhead. This process is sometimes called the Bernados process.

For carbon electrode welding, a voltage of about 35 volts is required. As in metallic electrode welding, the thicker plates require more current than the lighter ones. In carbon arc welding, usually about 300 to 450 amperes are used, although for light work, only 200 amperes may be used, and for very heavy work, about 800 amperes may be required. Contrary to the practice in metallic electrode arc welding, with a carbon electrode as long an arc as possible, usually about 1 to 1-1/2 inches, is held. This is to permit the oxidation of the carbon in the arc and so prevent its being deposited in the weld.

No other electric arc welding process is now in general use, although some others have been developed and used slightly. They are of experimental value, but have no bearing on the design

of commercial arc welding generators.

3. Arc Voltage and Current Characteristic Requirements. - Both alternating current and direct current are used for arc welding and both give good welds. A special transformer, instead of a special motor generator set, is required when alternating current is used. The alternating current apparatus has the advantages that it has no moving parts, no commutation trouble, it is light enough to be carried by hand and has a low initial cost. The disadvantages of alternating current are: The heat is equal at both electrodes while most of the heat is needed at the work; it cannot be used satisfactorily for carbon electrode welding for the carbon would be carried into the weld when the carbon electrode was the positive terminal; it requires a more skilful operator than does direct current due to the voltage dying down to zero every cycle; the weld is not likely to be so good, for, due to the difficulty of welding, the arc will be broken and started more frequently, which weakens the weld. As a result of these factors, direct current is ordinarily used where much welding is to be done.

It is well known that if a constant voltage is impressed on the electrodes of an electric arc light, the arc is unstable and to make the arc stable, it is necessary to work some adjustment so that the voltage across the arc will decrease as the arc current increases. The same thing is true of the electric arc in welding. A drooping volt-ampere curve is necessary to obtain a stable arc. Besides, the current should remain fairly constant when welding, in order to get a good weld. It is inevitable that

the operator will not be able to hold an arc of absolutely uniform length. If the voltage impressed on the electrodes were constant, the current would vary widely as the arc length changed. A drooping volt-ampere curve is necessary to minimize this effect.

For ease in welding, it is essential that the arc must not break if the length of the gap is suddenly increased. Otherwise, it would be almost impossible to either strike or maintain an arc. Another difficulty found in striking an arc is that often the metal electrode, when used, will weld to the work before it can be pulled away. If there is even a tending toward this, it is very difficult to start the arc, for the electrode, when broken loose, will probably be pulled away so rapidly and far as to break the arc. Even the slightest tendency of sticking of the electrode makes it difficult to start an arc.

4. Classes of Arc Welding Machines. - When alternating current is used for welding, a permanent adjustable resistance may be put in series with the arc and voltage taken directly from the alternating current lines, or the arc voltage may be taken directly from the secondary of a constant current transformer, the primary of which is connected directly across the line. Either type of apparatus may be used to reduce the voltage from the line voltage to that required by the arc, and to get the necessary drooping volt-ampere characteristic. These devices are used in doing alternating current welding from an alternating current line only.

If a direct current line is available, the arc current

used is always direct current, due to its better welding characteristics. The same adjustable resistance apparatus used for alternating current is also used for direct current welding. This apparatus is very satisfactory in every way except that it has a very poor electrical efficiency. For example, if operating from a 125 volt line, only 20 volts across the arc would be useful, and the 105 volts drop in resistance would be a dead loss. The electrical efficiency in this case would be 16%. If, however, the main line voltage were 500 volts, the electrical efficiency would drop to 4%. One of the types of apparatus developed to overcome this difficulty, whenever 125 volts is the potential difference of the supply lines, is the single operator dynamotor, which runs from a 125 volt line and is designed to supply the arc with the proper voltage and current from its terminals. Several of these are on the market and their electrical efficiency is high. They, however, come outside the scope of this discussion.

Another way of increasing the efficiency is to have a motor generator set deliver a lower voltage of a constant potential and use this, through the same resistance scheme as before, for welding. The voltage selected for these sets is usually 60 volts. A lower voltage than 60 volts would require so little resistance in series with the arc, that it might become unstable, and the short circuit current would become so excessive that it would tend to cause the electrode to weld to the work when starting the arc. A higher voltage would be less efficient. With this system, the overall efficiency, assuming the motor-generator set efficiency as 70%, would be $.7 \times \frac{20}{60} \times 100 = 23\text{-}1/3\%$, as compared

to the 16% for resistance alone when the current is taken directly from a 125 volt line, and the 4% when from a 500 volt line. It is obvious that such a motor generator set could be designed to run from any voltage direct current line, or any voltage alternating current line, and also that, inasmuch as the voltage is not affected by the load, several men could use the same generator at once as a source of power for welding. Consequently, this type of apparatus, called a multiple operator arc welding generator, is in wide use where several men are doing welding work at one place. However, this apparatus, too, is outside the scope of this discussion.

The single operator motor generator set is designed to give a higher electrical efficiency than can be gotten from welding by means of resistance only. It is designed to furnish directly to the arc the volt-ampere characteristics required for good welding. The special design is in the generator only. The motor can be designed to run from any type of power supply, whether alternating current, or direct current, and whatever the voltage. Since the generator is designed to furnish the volt-ampere characteristic for one arc, the voltage and current are interdependent and two operators could not satisfactorily weld from one generator, because the actions of one would seriously affect the power supply of the other. From the fact that these generators are designed for use by, and can only be satisfactorily used by, one operator at a time, these generators are called single operator arc welding generators. This class of generators is the subject of this special study.

PART II.

REQUIREMENTS FOR A SINGLE OPERATOR GENERATOR

5. Volt-Ampere Curve. - Although it is universally agreed that when a single generator feeds a single arc directly, and not through any resistance, the volts should drop as the resistance of the arc decreases, a wide difference of opinion still exists as to exactly the type of volt-ampere curve that is most advantageous. One opinion frequently presented is that the generator energy output should be constant while welding, regardless of arc resistance. This would mean that over the welding voltage range the product of the generator volts and amperes must remain practically constant. Such a curve is shown as Curve A in Figure #1. The principal advantage claimed for such a generator is that, with such characteristics, if the arc is made too long the current decreases to such an extent that the arc will break, and that if too short an arc is held, the current will become so large that it will melt away the electrode rapidly till the normal arc length is again reached, or, in other words, the arc length tends to be self-regulating. The proponents of such a generator claim that it forces the holding of a short arc.

The fact that the arc length is self-regulating is not in itself of great importance. It is important, however, that the arc be as short as possible, and that the material be melted and deposited at a uniform rate. Due to the fact that a generator must be designed for welding any of many different thicknesses of work, it is necessary to provide for easy and close adjustment

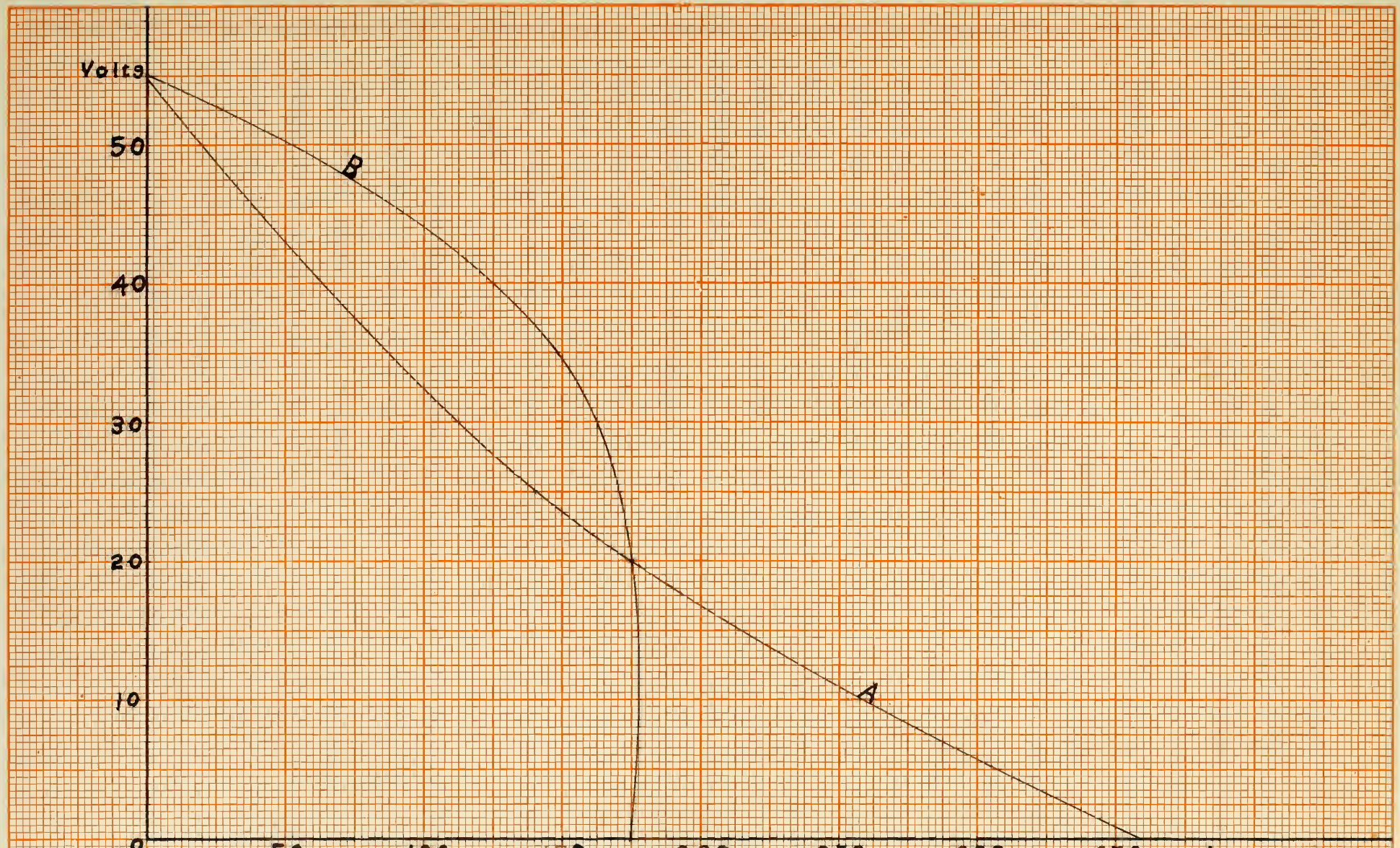

Fig. 1 - Types of Welding Generator Curves. - (A) Constant Energy, (B) Constant Current.

of the welding current any place within the range of the generator, and this range is usually made from about 75 amperes welding to 175 amperes welding. In a constant energy generator, it is evident that with a given adjustment of the generator, and with a given electrode, the arc will tend to maintain a certain length. There is no reason for thinking however that this is a short arc. It is likely to be a long arc as a short one. This supposed advantage then does not exist. This generator, however, has three real disadvantages. Due to the fact that lengthening the arc tends in a high degree to cause the arc to break, it is very difficult for any one other than an experienced welder to use such a machine. Also, when the electrode touches the work in striking the arc, the short circuit current is so high that it tends to weld the electrode to the work, thus making the starting of the arc difficult. Furthermore, as the arc length changes, the current changes greatly and, as found by experiments of the Research Department of the Westinghouse Electric and Manufacturing Company, this change of current causes the electrode to melt and deposit at a varying rate, which is detrimental to the weld.

The Research Department of the Westinghouse Electric and Manufacturing Company found, as a result of tests that to get uniform metal deposition, regardless of the arc length, it was necessary to have an approximately constant current through the arc. On first thought, it would seem that to melt iron at a uniform rate, a constant amount of heat could have to be generated in the arc, or a constant energy generator required. However, as the

arc is lengthened, more heat is radiated and to keep a constant amount available for melting the iron, approximately a constant current is necessary. A uniform flow of welding metal is then one advantage of a generator designed for a constant current over the range of welding voltages. Considering ease of operation, the constant current generator is superior to the constant energy generator, as an increase in arc length does not tend to break the arc when judged from the volt-ampere curve alone. Furthermore, it does not have so great a tendency to cause the electrode to stick on starting the arc, for, with the same welding currents in both cases, the short circuit current of the constant energy generator far exceeds that of the constant current machine. Any length of arc can be used with a constant current generator, as well as with a constant energy generator. Curve B of Figure #1 is a typical volt-ampere curve of a constant current arc welding generator.

6. Speed of Action. - If, when welding, the length of arc is suddenly increased, the current through the arc will momenturily die down and then build up again. It may even die down enough to break the arc. This will happen even with constant current generators where the steady current was the same for the original and final length of arcs, and all lengths between. It is evident that for ease of operation, these transient deviations from the normal steady conditions should be minimized as much as possible, both as to the magnitude of the deviation and the length of time it lasts. This is essential, for otherwise, regardless of the shape of the volt-ampere curve, inasmuch as it is impossible to always hold an arc of uniform length, the current will always be rapidly increasing or decreasing, the rate of material deposition will

not be uniform, and the arc will break frequently. Also when a single operator generator is short circuited in starting an arc, the short circuit current will build up to a value greater than the steady short circuit current, and then will die down to that value. This deviation from normal short circuit current should also be minimized, as an excessively high current tends to cause the electrode to stick to the work. To reduce these variations, it is necessary to have a fast field, so that after any change in arc length, the main pole flux will reach to its steady value as soon as possible.

7. Inductance. - Another condition that usually will give much the same effect as a fast field, is to have high inductance in the armature circuit. This inductance may come from the generator itself or may be a separate external inductance. Inductance in the armature circuit reduces the transient variations, tends to hold the current steady, and so makes for ease in welding. In this way, it may act as a partial substitute for a fast field. When striking the arc, however, the inductance will tend to prevent the current from exceeding normal, but it also causes the current to build up to normal slowly, which is not desired.

8. Efficiency. - A high electrical efficiency is desirable in a welding generator, but its importance is frequently overestimated. The cheapest generator is the one which will do the most welding with the least total cost. Assuming an arc welding motor generator set overall efficiency of 55%, a power cost of 3 cents per kilowatt hour and an average generator output of 2.2 K.W., the cost of power for one welder would be 12 cents an hour. The welder's time probably would cost 75 cents an hour. If by

any change in design of the generator the welder were enabled to do 10% more work than before, the saving in the amount paid the welder would justify a decrease in the motor generator electrical efficiency from 55% to 35%. Electrical efficiency is, therefore, a poor criterion of the worth of an arc welding generator.

9. Commutation. - A single operator arc welding generator is subject to high peak currents. To care for these peak currents and the rapidly fluctuating load satisfactorily, the commutation characteristics of the generator should be very good.

10. Simplicity. - To reduce the probability of incurring trouble with the generator and to facilitate the generator's repair when it does give trouble the generator, its panel, and all connections should be as simple as possible.

11. Size. - The generator and its auxiliary equipment should be as small and light as is consistent with good design. Such a generator, with its auxiliary equipment and driving motor, is often mounted on trucks and should be light enough to be handled with ease, and should be small in dimensions so that it can be moved readily through crowded shop aisles.

12. Portability. - As the generators and auxiliary equipment are often mounted on trucks and hauled around, the mechanical design of the equipment should be made with such service in view. All parts should be designed for portable service.

13. Cost. - For commercial reasons, it is essential that the first cost of the welding generator and auxiliary equipment be as low as is consistent with good design.

PART III.

RELATION BETWEEN THE GENERATOR CHARACTERISTICS DESIRED AND THE GENERATOR DESIGN.

14. Volt-Ampere Curves. - In designing a single operator welding generator, the method of attack is usually to design to obtain the desired volt-ampere curves and then to modify this design in such a way as to obtain the other characteristics desired. The important differences in the various types of machines are those due to the different methods of obtaining the desired volt-ampere curves.

Ordinarily, in the design of a generator to get any desired volt-ampere curve, the designer may make use of seven different means of shaping the curve. He may use, if he desires, a separately excited field, a self-excited shunt field, a series field, either addative or differential, and may select such a saturation curve as he desires.

These are his four chief means. He may also make use to a much smaller degree of shifting the brushes from neutral, making the commutating pole winding either too strong or too weak, and increasing the distorting effect of the armature ampere turns. If the generator is made a freak, as for example using a four pole stator with a two pole rotor, further possibilities of variation of the volt-ampere curves are found.

The ideal volt-ampere curves to be produced by the different adjustments of a single operator generator are shown in Figure #2.

In Figure #3 is shown the typical volt ampere curves of a separately excited generator, a shunt wound generator self-excited,

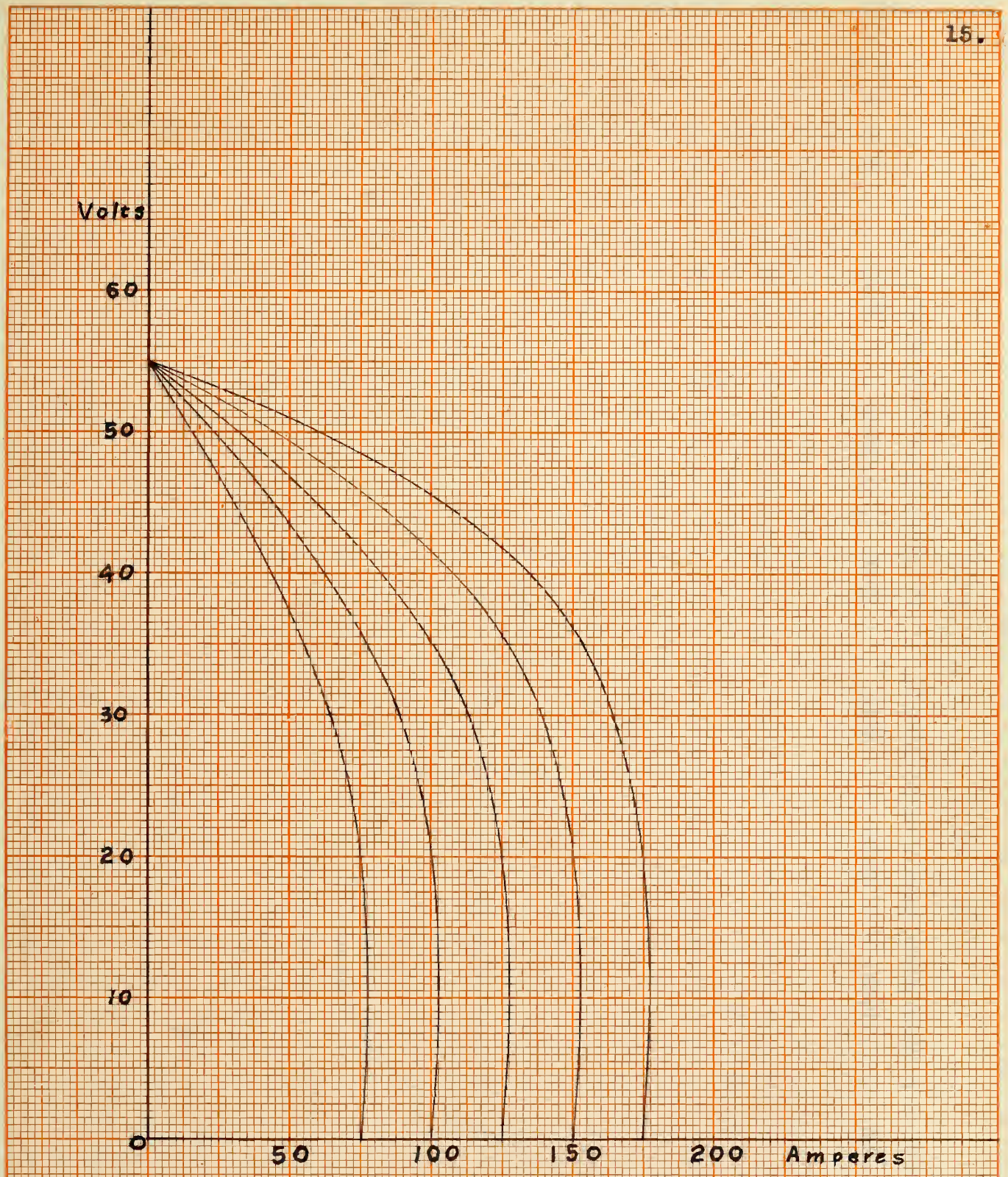

Fig. 2 - Welding Generator Curves Desired.

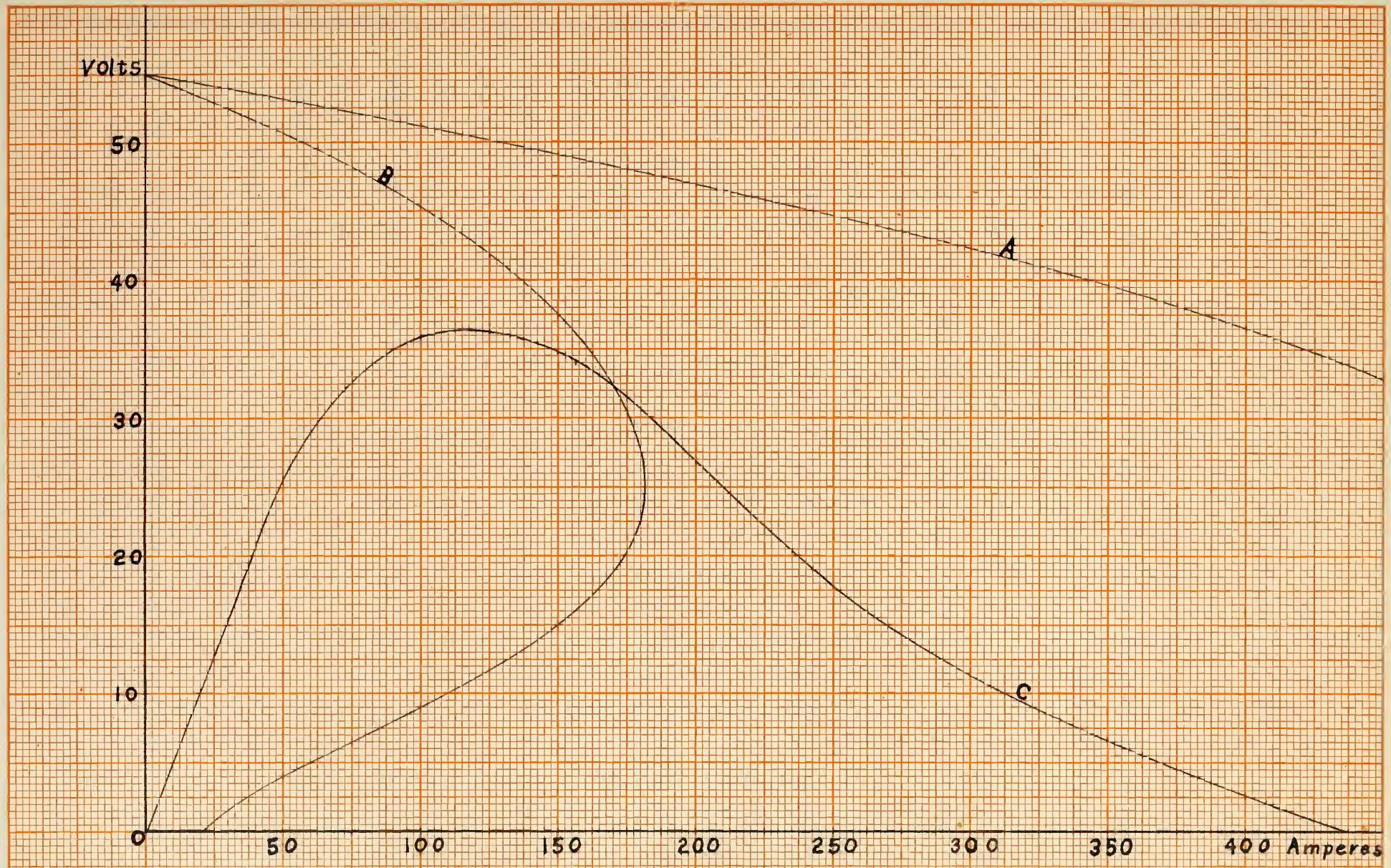

Fig. 3 - Generator Regulation Curves - A, Separately Excited; B, Shunt Wound; C, Series Wound.

and a series wound generator. The various combinations possible of these windings, with their advantages and disadvantages, will be discussed later.

When working high on the saturation curve, as load is applied, the voltage does not decrease so rapidly as when working on the straight line part of the curve. To obtain the type of volt-ampere curves desired, then, the generator should be saturated at no load, but unsaturated at welding voltage. The curve resulting, would be approximately as shown in Figure #2.

Shifting brushes slightly from neutral gives approximately the same effect as the addition of a series field. A shift in the direction of rotation gives the effect of a differential series. A shift in the opposite direction gives the effect of an addative series. The effect to be gained in this way is limited, for if the brushes are shifted far from neutral, commutation will become bad. In the same way, if the commutating coil strength is made more than is required for best commutating conditions, the resultant circulating currents flowing in the coils short circuited by the brush have much the same action on the main pole flux as would an addative series on the main pole itself. Making the commutating coil too weak, would have an effect similar to using a differential series coil. Here again, commutation is a limit.

When a generator is loaded, the armature ampere turns increase the flux at one tip of each pole and decrease the flux at the other tip. Due to the shape of the iron saturation curve, the increase of the flux is not so great as the decrease and, as a result, the total flux through the pole is decreased by the

armature distorting ampere turns. This reduction of flux is increased by using a smaller air gap and decreased by using a larger gap, but it is not possible to vary this reduction much by such means.

15. Speed of Action. - The speed of the field action is secondary in importance only to the volt-ampere curve of a single operator arc welding generator. Two conditions must be obtained if after a change of arc length, the arc voltage and current are to quickly reach their steady value. The first condition is that the main pole flux changes must be damped as little as possible. Damping of the rate of flux change cannot be entirely eliminated. The most effective dampers on the rate of flux changes are the shunt field windings.

With any definite rate of change of flux in the main poles, the volts induced in all the shunt coils connected in series, is KN.

Where K is a constant depending on the rate of flux change and the number of coils in series,

and N is the number of turns in each of the shunt coils. Also, the damping current caused to flow by such voltage is $\frac{KN}{R}$, where R is the resistance of the shunt field circuit. The damping ampere turns per coil then would be $\frac{KN^2}{R}$. These ampere turns are superimposed directly on the ampere turns from the steady excitation voltage.

To obtain little damping action from any shunt coil, then it is necessary that that shunt coil circuit have a high resistance and that it have few turns interlinking with the magnetic circuit. The resistance of the coils themselves would be $\frac{N}{K_1 A}$, where K_1 is

approximately a constant, and is dependent on the coil dimensions, and number of coils in series, and A is the cross section of the conductor. Then, not including any external resistance in series with the coils, the damping ampere turns would become KK_1NA. But NA is the total cross section of copper in a coil, and therefore the damping action is proportional to the cross section of the copper in the coil, if no external resistance is used. On account of the damping action, the cross section of all shunt coils should be made as small as possible. Such reduction, however, is limited. A definite number of ampere turns is required from each coil and the current density in the coil is limited by heating. The coil ampere turns in a given machine are practically proportional to coil copper cross section times current density in the coil. When the density is made as high and the ampere turns as low as permissible, the cross section of the coil is a minimum, and the damping action of the coils can no longer be reduced without the use of external resistance.

It is evident that if an external resistance of an amount equal to the total resistance of the coils in series is placed in series with the coils, and if the excitation voltage is doubled to correspond, the ampere turns and density remain unchanged, but the damping ampere turns are halved. Let the ampere turns required divided by the current density be K_2NA, where K_2 is a constant depending on units used. Then the damping ampere turns, with no external resistance used is $\frac{KK_1}{K_2} \times \frac{\text{Ampere Turns}}{\text{Current Density}}$. Letting R be the resistance of all such coils in series, and Rx be the total external resistance in series with these coils, then the damping ampere turns, when using external resistance, are

$\frac{KK_1}{K_2} \times \frac{\text{Ampere Turns}}{\text{Current Density}} \times \frac{R}{R+Rx}$. However, the addition of the external resistance entails extra losses and so reduces the generator efficiency.

The relation found above holds true whether the shunt is self excited or separately excited, and for any voltage of excitation. If the ampere turns are taken as the total ampere turns in the generator due to that shunt circuit, and R is taken as the total internal resistance, as coils are finally connected, then the relation also holds true regardless of whether all coils are in series, all are in parallel, or there is a series parallel arrangement. If two separate shunt circuits are in the generator, as a separately excited field and a self excited field, then the damping ampere turns of the two must be added to get the total shunt damping ampere turns.

The series coils also conform to the same relation as the shunt coils. However, the external resistance, all resistance in the armature circuit, is usually so high that $\frac{R}{R+Rx}$ is so small that the series damping action is negligible. If the series coils are shunted Rx may become small and then the series coil damping action may become important.

The armature coils short circuited by the brushes also interlink with the main pole flux, and form a closed circuit, and so act as dampers. Due to the fact that the turns involved are few, and the brush contact drop is high compared to the resistance of an armature coil, it is probable that the damping effect of the short circuited armature coils is negligible.

If the brushes are off neutral the armature will have

an additional damping effect similar to that of the series coils, and negligible for the same reasons.

The iron parts of the magnetic circuit also tend to damp out any changes in flux. A flux change sets up eddy currents in the iron which tend to prevent the change. By laminating the iron such eddy currents are largely eliminated. In all modern generators the armature and main poles are laminated. Laminating the frame, also, should tend to reduce the damping action, but, as iron gives a very high resistance patch to eddy currents, the damping effect of the generator frame is probably negligible. Certainly it is not of the magnitude of the damping effect of the shunt coils. Consequently, it is doubtful if laminating the frame is justifiable.

The second factor affecting the speed of the change of flux is the ampere turns on the generator available, for causing an increase or decrease of flux, at each instant during the time the flux is changing from one steady value to another. A generator in which the flux change is dependent on the change of a self excited shunt field excitation will be extremely slow in action, for an increase in generator voltage results in turn in an increase of excitation, an increase in flux, and an increase in voltage, and so on around the circle. The increase of excitation comes slowly, and by small increments, and therefore the flux builds up slowly. This is such a well known condition that no explanation is necessary.

If the flux change is due to the change of current through a differential series field the action should be extremely rapid. Assume that the arc is suddenly lengthened while welding, then

the current will suddenly drop to an amount less than the final steady welding current at exactly the same time the net field ampere turns increase till, at the instant the final steady welding current is reached, the field would have reached its final ampere turns, except for the damping effect of the separately excited field. Due to this damping effect, the separately excited field ampere turns will be less than the final steady value, and so the current continues to decrease further. However, the rate of change slows up, the damping effect decreases, and, as the separately excited field overcomes the damping effect, the current increases and the differential series field approaches its final value. On the other hand, if the arc is suddenly short circuited the differential series ampere turns will increase exactly as does the armature current, and when the armature current overshoots the final value, so will the differential series. It can be seen that the differential series field is ideal for getting quick flux changes for it acts exactly at the instant the current changes, acts always in a way to bring the current to its final steady value, and the magnitude of the magnetomotive force due to the series tending to bring the flux to normal, is always proportional to the amount the current is different from normal.

An addative series field acts in every way the exact opposite of a differential series. When the current decreases, it causes the field flux to reduce, but it should be doing the reverse. When the current increases, it causes the field flux to increase, but it should decrease, and must before a stable welding condition is reached.

Shifting brushes from neutral, and making the commutating coil too strong, or weak, has the same effect as the use of a series field, as explained previously.

Summing up, in order to obtain rapid flux changes, the principal points to be observed are:

(1) Use as low a maximum total shunt field ampere turns as possible.

(2) Use as high a current density in the shunt field as possible.

(3) Use as much external resistance in series with the shunt fields as permissible.

(4) Use as strong a differential series field as permissible.

(5) Avoid using any self excited shunt fields in which the excitation is caused to change by a change in arc length.

(6) Do not use an addative series field.

The excitation of a separately excited shunt field does not change with the change of arc length, so the only effect such a field has on the speed of flux change is its damping effect.

16. Inductance.- When an armature is loaded a strong cross magnetic flux is set up. This flux enters one tip of each pole, traverses the pole to the other pole tip, crosses the air gap to the armature and returns through the armature core. This cross magnetic flux is approximately proportional to the armature current and interlinks with many of the armature conductors. It is evident that this flux makes the armature inductive and that as the main pole airgap becomes smaller the cross flux, and, in

turn, the armature inductance increases. As the armature turns increase both the flux and turns interlinked increase, and so the inductance is approximately proportional to the square of the armature turns. This presupposes that the pole tips are not sufficiently saturated as to materially reduce the cross flux. The poles should be designed so that, with the maximum possible cross flux, there would be no pole tip saturation.

A second, although much less important, source of inductance is the series field. In general, as the armature current increases the field flux decreases, and vice versa. It is desired to keep the armature current constant. The inductive voltage set up in a coil by the change of flux interlinking with that coil is always such as to tend to cause such a current to flow in the coil as would tend to prevent a change of flux. Assuming these three things, it is evident that when a differential series field is used:

(1) An increase of current causes a decrease of flux.

(2) A decreasing flux sets up an induced voltage in the series coil.

(3) This induced voltage tends to cause current to flow in such a way that it will magnetize the field, opposing the load current.

(4) Therefore this induced voltage tends to keep the armature amperes from increasing.

This coil differs in action from an ordinary inductance, in that the flux is not proportional to the coil current. Otherwise, the effect is the same. In an addative series field used on a generator in which the flux decreases with an increase of load

the induced voltage tends to increase the series coil current, and so the effect is the reverse of inductive.

A third source of inductance is the slot flux. Flux leaks across the top and through the middle of a slot and interlinks with the armature coils. This interlinkage adds to the total inductance of the armature. It can be increased by deepening the slot and making it narrower, but such change tends to cause a higher reactance voltage and make the commutation bad, so in actual design no attempt is made to increase armature inductance in this way.

A fourth source of inductance is the commutating pole flux. The commutating pole flux interlinks with the commutating pole turns and with the armature conductors. It has an inductive effect on the commutating pole coils but the effect is reversed on the armature coils. As the total commutating pole coil turns always exceed the effective armature turns, the net result is that there is an inductive effect from the commutating pole flux, and this effect can be made a maximum by using the maximum possible length of commutating pole gaps, with the resultant large number of commutating pole turns.

17. Commutation. - To insure good commutation, the arc welding generator should be a commutating pole machine. It is advisable for such service to use as many commutating poles as main poles. Care should be taken to get the proper shape of commutating pole face and to obtain the right commutating coil strength for the gap used. The brushes should be set approximately on the mechanical neutral. The current density in the brush contact surface should not be excessive. The commutating zone should not be too large a part of the neutral zone.

In all the following diagrams for simplicity the commutating pole coils are not shown, although they should be used in all cases.

18. Size. - All of the other listed requirements of a good welding generator (except simplicity, of which nothing further will be said) are closely related to the size.

The size of a generator depends very directly on its efficiency. The losses that can be dissipated by an armature, without exceeding a given temperature rise, are approximately proportional to the diameter of the armature core multiplied by its length. Therefore the less efficient the generator is the greater are its losses, and, consequently, the larger must be the machine.

Assuming the same general construction, the larger the generator the greater will be its cost.

Although both size and method of construction effect the portability of a generator, it is evident that a generator must be small if it is to be portable.

Since size is important, it is desirable that the minimum possible size be determined. Every generator is expected to deliver a definite voltage at a certain speed. It also will have a definite current which it must deliver for a certain length of time, without exceeding a fixed temperature rise. The normal single operator arc welding generator is usually expected to deliver about 55 volts at no load continuously, and to deliver about 175 amperes at 20 volts for one hour without exceeding a temperature rise of 50° C. Taking such a generator as an example, it is seen that the generator must have a flux capacity, when fully saturated,

sufficient turns on the armature, to give 55 volts at the speed the generator is to be driven. Also, the armature conductors must be of such a size that the armature will carry 175 amperes without exceeding the temperature guarantees. The size of this machine would be practically the same as a standard shunt motor having an input of 175 amperes and a terminal voltage of 55 volts and no load speed the same as the speed of the generator. Assuming a motor efficiency of 85% and that the full load speed of the motor would be 92% of the no load speed, then such a generator would correspond to a motor with an output of $\frac{175 \times 55 \times .85}{746}$ horsepower, or about 11 horsepower, at 92% of the generator speed. The size motor to do this would also deliver 12 horsepower at the generator rated speed, and that size machine is the smallest that could be used to get the specified performance.

If other voltages and amperes are required, the smallest standard size machine that can be used may be determined in the same way. The rating worked out, 55 volts no load, 175 amperes welding, is a normal single operator generator rating but other ratings are sometimes used.

It should not be inferred that all generators are made the minimum size possible for their rating. Very few are so small. Most welding generators have had their size increased over the minimum, due either to the type field windings used, the attempt to get a high inductance, or to use a standard armature with a long enough commutator to carry the rated current. However, the smallest possible size is a standard against which the actual sizes may be checked, and for comparison will be referred to hereafter as the standard size generator.

PART IV.

TYPES OF SINGLE-OPERATOR GENERATORS

19. Separately Excited Generators. - One of the simplest of the types of generators that could be used for arc welding is a separately excited generator. Such a generator might be designed for use with an external resistance in series with the arc, or for use without such a resistance.

If the generator is designed for use without external resistance, the resistance of the generator itself must be sufficient to cause the drop from no load voltage to welding voltage. With a definite no load voltage, as the resistance is fixed, a definite welding current would result. In this, and all other types of welders, it will be assumed that the maximum no load volts required are 55 and the maximum welding current at 20 volts is 175 amperes. Then such a generator must have enough resistance in the armature, commutating pole coils, and brushes, to cause a drop of approximately 35 volts with 175 amperes flowing. This would result in a loss of approximately 6125 watts in the generator itself. The minimum size generator was taken as one which should have 85% efficiency on a basis of 55 volts output, or the losses there would be $\frac{175 \times 55 \times 15}{100}$ watts or 1444 watts. Since the losses that can be dissipated with a given rise by generators are approximately proportional to the diameter times the length of the armature core, then a separately excited generator used without external resistance would require an armature having a diameter and length each about twice that of the standard generator. It would then actually be eight times the size.

Inasmuch as for welding practice the generator must never have a no load voltage below 35 volts, as this is necessary to strike the arc, it can be seen that the minimum possible welding current would be 110 amperes. It is usually desired to be able to go down to 75 amperes.

The volt-ampere curve that would be gotten is shown in Figure #4, and is entirely satisfactory. It is a straight line curve, which is a mean between the constant energy and constant current curves. Such a machine would have little flux change so it is not affected by the speed of flux change. Since it has no flux lag it needs little inductance. What inductance is required is simply to prevent the current building up to such a value, when the electrode is touched to the work, in starting the arc, as will weld the electrode to the work. As can be seen from Figure #4, the short circuit current far exceeds the welding current. Such a generator is very inefficient for under maximum current conditions, the efficiency is approximately $\frac{20 \times 100\%}{55}$ or 36%. Due to its size it is costly and not very portable.

Such a generator, however, is simple and requires little auxiliary apparatus. Aside from voltmeter an ammeter, and a knife switch, which are required for all generators, all that is required is a source of separate excitation, a field rheostat, and possibly a reactor. This type of generator has never been made commercially for arc welding.

The separately excited generator designed for use with external resistance is designed to be as small as possible and to have an external resistance use up the difference between the generator volts and the welding voltage. The generator will be

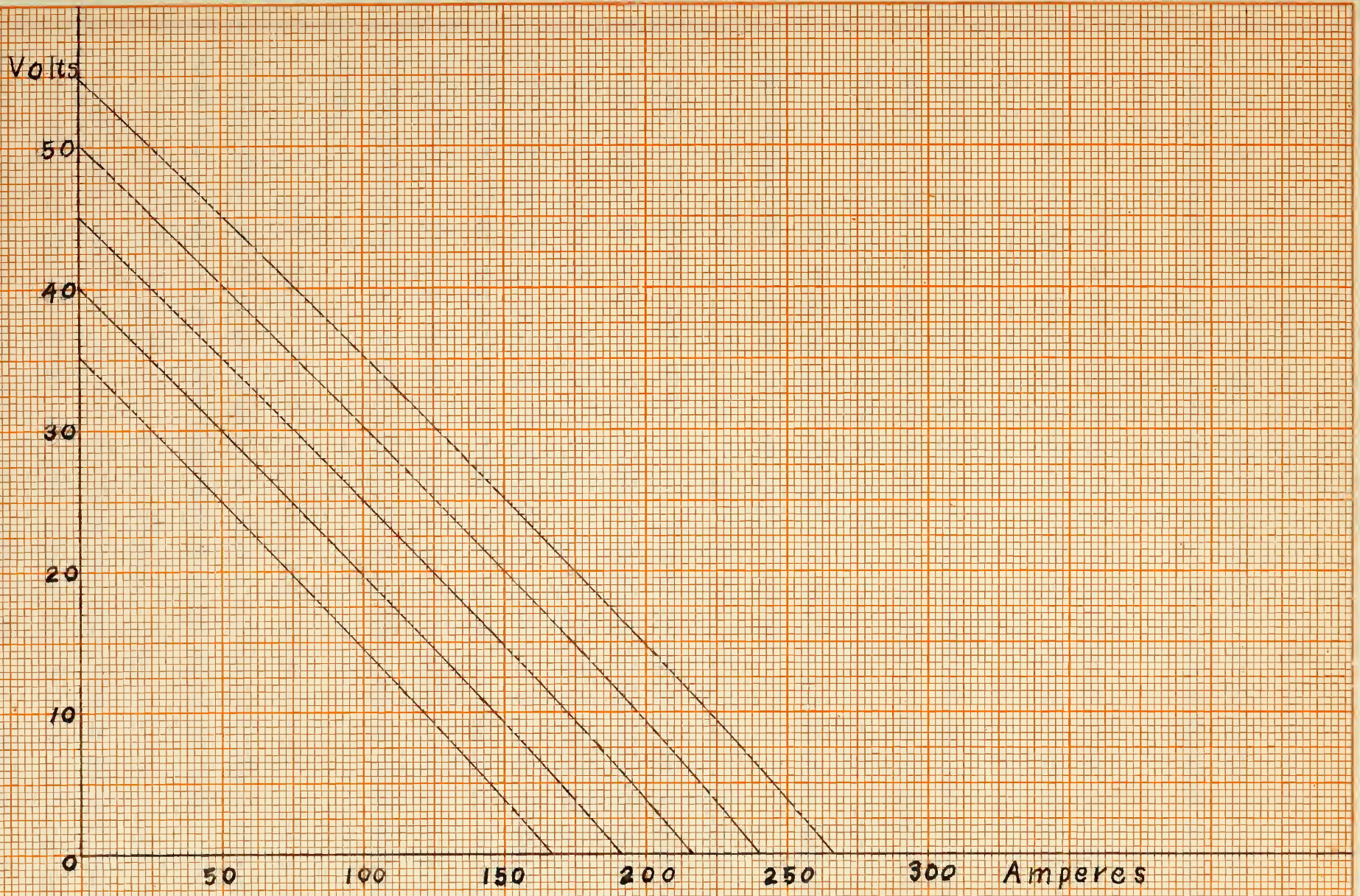

Fig. 4 - Separately excited high resistance generator curves.

as small as the standard generator. It is very simple, and therefore cheap and portable. The generator efficiency is high but the total efficiency when resistance losses are included is again about 36%.

The field flux does not change appreciably, and so speed of flux change need not be considered. Little inductance is required, and that only because of the high short circuit current. Since practically all of the voltage decrease is due to resistance drop it can be readily seen that, neglecting the inductive effects, the voltage increases almost exactly as the current decreases.

The volt-ampere curves of such a generator are shown in Figure #5. These are desirable curves.

Such a generator requires for auxiliary apparatus, aside from a voltmeter and ammeter, a field rheostat, an adjustable cast grid resistance, with knife switches, and possibly a reactor. The big steps of welding current would be obtained by varying the resistance in the armature circuit by means of the knife switches, and the finer adjustments would be gotten by means of the field rheostat. Also a separate source of excitation must be available. This generator has never been built commercially for welding service.

20. Shunt Wound Self Excited Generators. - If a shunt wound self excited generator is short circuited the current dies down to a low value, the terminal voltage becomes zero and there is no current through the shunt field. Then if the short circuit is quickly removed, as in starting an arc, there is not sufficient current flowing to start an arc, and there is but little induced voltage to start it. As a rsult the arc breaks. To overcome

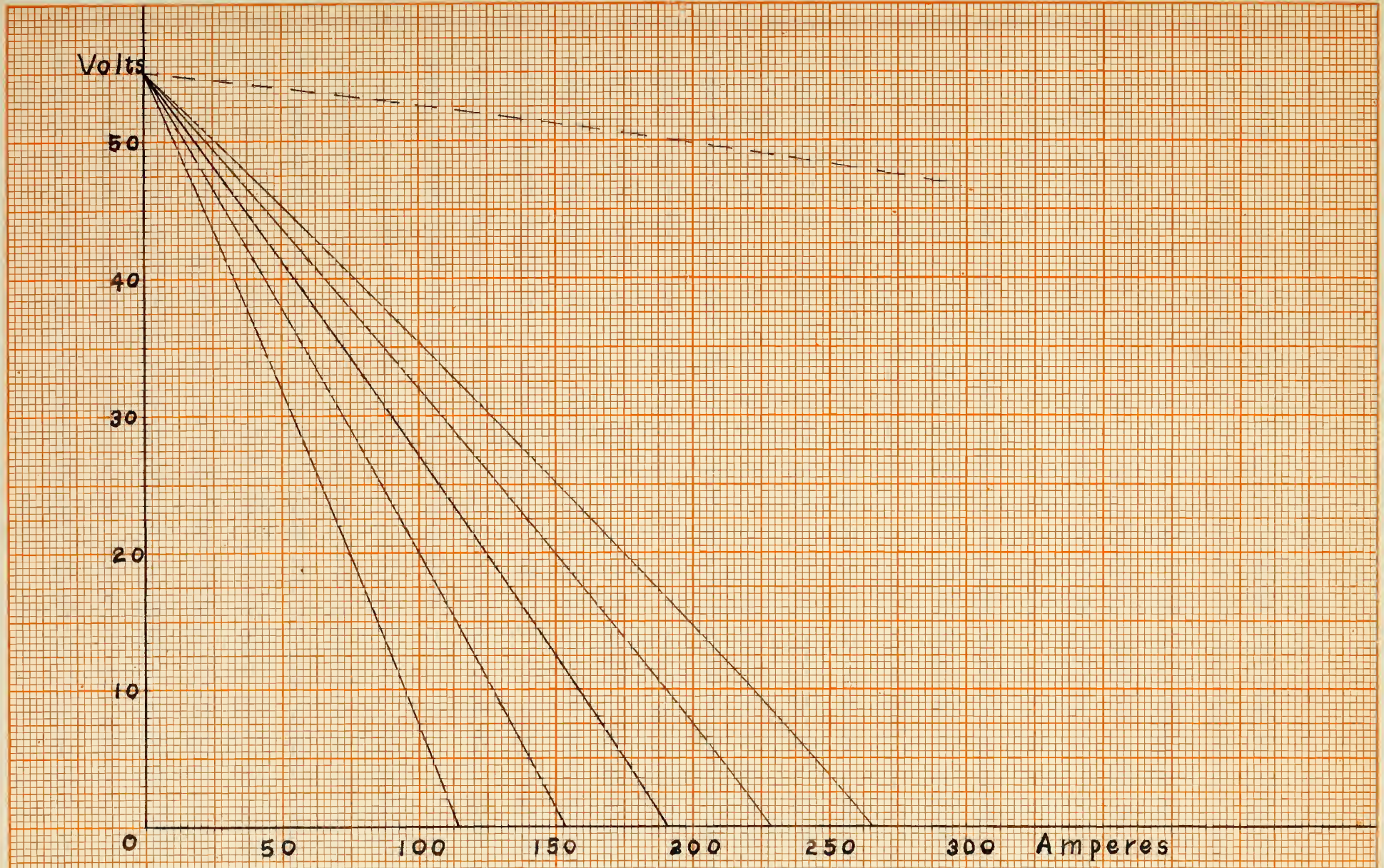

Fig. 5 - Curves from a separately excited generator using an adjustable external resistance. Generator curve is broken. Arc curves are solid.

this it is necessary to put a resistance in series with the arc, and also in most cases, to put a reactor in series with it. The greater is the resistance the larger will be the short circuit current with the same field setting, and the smaller need be the inductance of the reactor. Two general types of self excited shunt wound generators with external resistance can be used for arc welding.

One type of self excited shunt wound generator has characteristics similar to those of the separately excited generator using external resistance. It has the shunt field adjusted to give approximately 55 volts no load, and the big step adjustments of the welding current are made by varying the resistance in series with the arc, and the finer adjustments made by use of the field rheostat. Part of the drop from 55 volts to 20 volts comes from the natural voltage drop of a shunt generator, but the major part comes from the drop in the external resistance. Since part of the drop of the voltage is due to a decrease in flux the efficiency would be somewhat above 36% and the response of the voltage to change of current would be a little slower than in the case of the separately excited generator.

Like the separately excited generator with external resistance, this generator is the minimum possible in size and cost, is portable and simple. Due to the lag of the shunt field, it will need more inductance than the separately excited generator. It will require exactly the same auxiliary apparatus except that no separate source of excitation is required. Its volt-ampere curves are practically the same as those of the separately excited generator with external resistance, shown in Figure #5. Such a

generator has never been manufactured commercially for arc welding use.

The second type of the self excited shunt wound generators is one with which enough external resistance and reactance is used to enable an arc to be struck. The external resistance is constant in value and the drop in voltage is principally the result of the inherent drooping characteristic of the shunt generator. The current adjustment is made by means of the shunt field rheostat. The no load voltage varies widely but would probably not be below 35, when adjusted for 75 amperes welding current.

Such a generator, shunt wound, not very highly saturated and with a wide range of flux values, would necessarily have such a sluggish field that it could not compete with other types. Due to this sluggishness, it would require a highly inductive reactance in series with the arc. It would, however, be comparatively efficient, for much of the voltage change is the result of the change of flux, instead of resistance drop. It is more simple than the first self excited generator described, for it uses a constant instead of an adjustable resistance. Otherwise the same auxiliary apparatus is used.

Such a generator would be slightly larger, probably about 20%, than the standard generator, for it could not be worked at as high a degree of saturation as iron can be worked. If the saturation be too high, the voltage at the generator terminates will not drop sufficiently upon the application of load. The less saturated a generator is, the more will its voltage decrease, in percent, upon the application of a given load.

The increase of size results in an increase of cost and decrease of portability.

The volt-ampere curves of such a generator are shaped practically the same as the curve for the self excited shunt wound generator shown in Figure #3. Such curves are not very desirable, for, due to the shape of the lower part of the curve, usually not enough short circuit current will flow to quickly heat a spot on the work to the melting point. Further curves are not drawn out for this generator because the machine is not desirable, on account of its sluggishness, the high inductance required, its size, and its volt-ampere curves. It has never been built commercially for arc welding service.

21. Self Excited Addative Compound Wound Generators. - Two types of self excited addative compound wound generators are actually in use. In the first type the generator is saturated magnetically at no load, sufficient compounding is used to keep the voltage constant regardless of load, and an external resistance is used to reduce the voltage at the arc to twenty volts. In the second type the generator is comparatively unsaturated at no load and has enough series to produce the desired welding current, no external resistance being used.

Two varieties of the first type are used. In one variety an adjustable resistance is used in series with the arc. A diagram of the generator is shown in Figure #6. For simplicity, and to show the difference between the different types of generators, all diagrams are made as schematic as possible, and such things as are used on all generators, as commutating coils, meters, line switches and reactors, are omitted from the figure. Its volt-

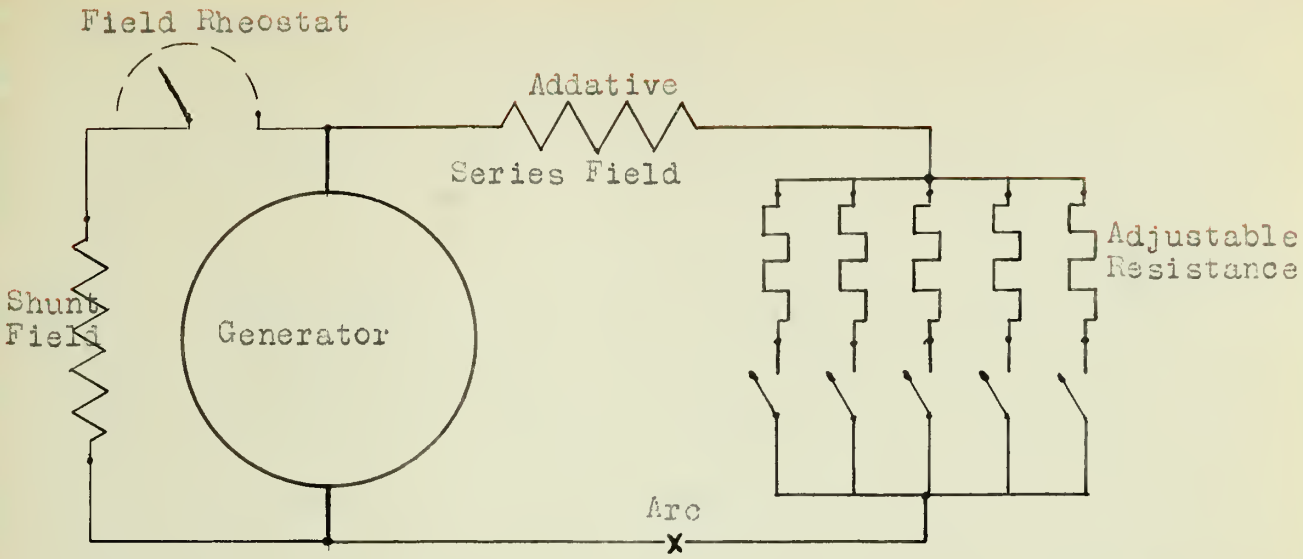

Fig. 6 - Diagram of a self excited addative compound wound saturated generator using an adjustable external resistance.

ampere curves is the same as those shown in Figure #5. This generator is the standard size, the cheapest and the most portable of arc welding generators. It however has an efficiency of only about 36%, when resistance losses are included, and the cast grid resistances are not very portable. Such a generator is simple, its flux changes but little, so speed of flux action is not important, and only enough inductance is required to keep the electrode from sticking to the work, when striking the arc. Its volt-ampere curve is satisfactory. The auxiliary apparatus required is a voltmeter, an ammeter, a rheostat, adjustable resistances, with controlling knife switches, and a reactor. This type of generator is now used by most manufacturers when several operators are to use the same generator and formerly was manufactured for use as a single operator generator. Due to its poor efficiency, it

has recently been largely replaced with other types of apparatus.

The other generator of the first type uses a varying resistance in series with the arc instead of a permanent adjustable one.

This varying resistance consists of a carbon pile and is varied by means of special control in such a way that the current remains approximately constant. Such an outfit presents a problem in control design rather than generator design and so is of little importance in the present discussion. So far as generator characteristics are concerned, excepting only the volt-ampere curve, this generator is exactly the same as the first variation considered. This type of apparatus is manufactured by the Wilson Welder and Metals Company, Inc., under the name of the Wilson Plastic Arc Welder. As a matter of interest, it may be stated that the Wilson Welder is designed to produce only 35 instead of 55 volts. This results in a much smaller generator than standard and also gives a much better efficiency, about 50%. However, due to its low voltage, such generator cannot be used for carbon electrode welding, for metallic electrode welding where the electrode has a heavy coating, nor where excessively long leads, of a high resistance reach from the welding panel to the work.

The second type of self excited addative compound wound generator is not designed to give a definite voltage at no load. The welding current is adjusted by adjusting the strength of the shunt field by means of a rheostat, and by changing the strength of the series field. The no load voltage is determined by the shunt field alone. The short circuit current is determined by the series field alone. By the adjustment of both fields a volt-

ampere curve can be produced through almost any two points desired. The rest of the curve, however, cannot be controlled.

In actual practice the big changes of welding current would be obtained by a change of series field strength and the finer adjustments made by varying the shunt field strength. The volt-ampere curves of this generator are shown in Figures #7 and #8. Figure #7 shows the effect of varying the series field alone. Figure #8 shows the effect of varying the shunt field alone. These curves are satisfactory as long as the no load voltage is not too low. The curves with an extremely low no load voltage are not very desirable.

This type of generator has very wide changes of flux. Its fields consist of a shunt winding, which is extremely sluggish, and an addative series winding, which was found to have characteristics that tended to reduce the speed of flux change. As a result, such a generator probably would have a very slow rate of flux change, with a resulting necessity for the use of a highly inductive reactor in series with the arc.

The efficiency of such a generator is high, and it is simple in construction. Due, however, to the fact that it cannot be highly saturated, and produce the volt-ampere curves desired, such a generator would be slightly larger, probably about 20%, than the standard generator, and its cost would increase and portability decrease correspondingly.

The auxiliary apparatus required is a knife switch, a voltmeters, an ammeter, a reactor, a rheostat, and a means for adjustin the strength of the series field. Taps could be brought out from the series field and means provided, either knife switches

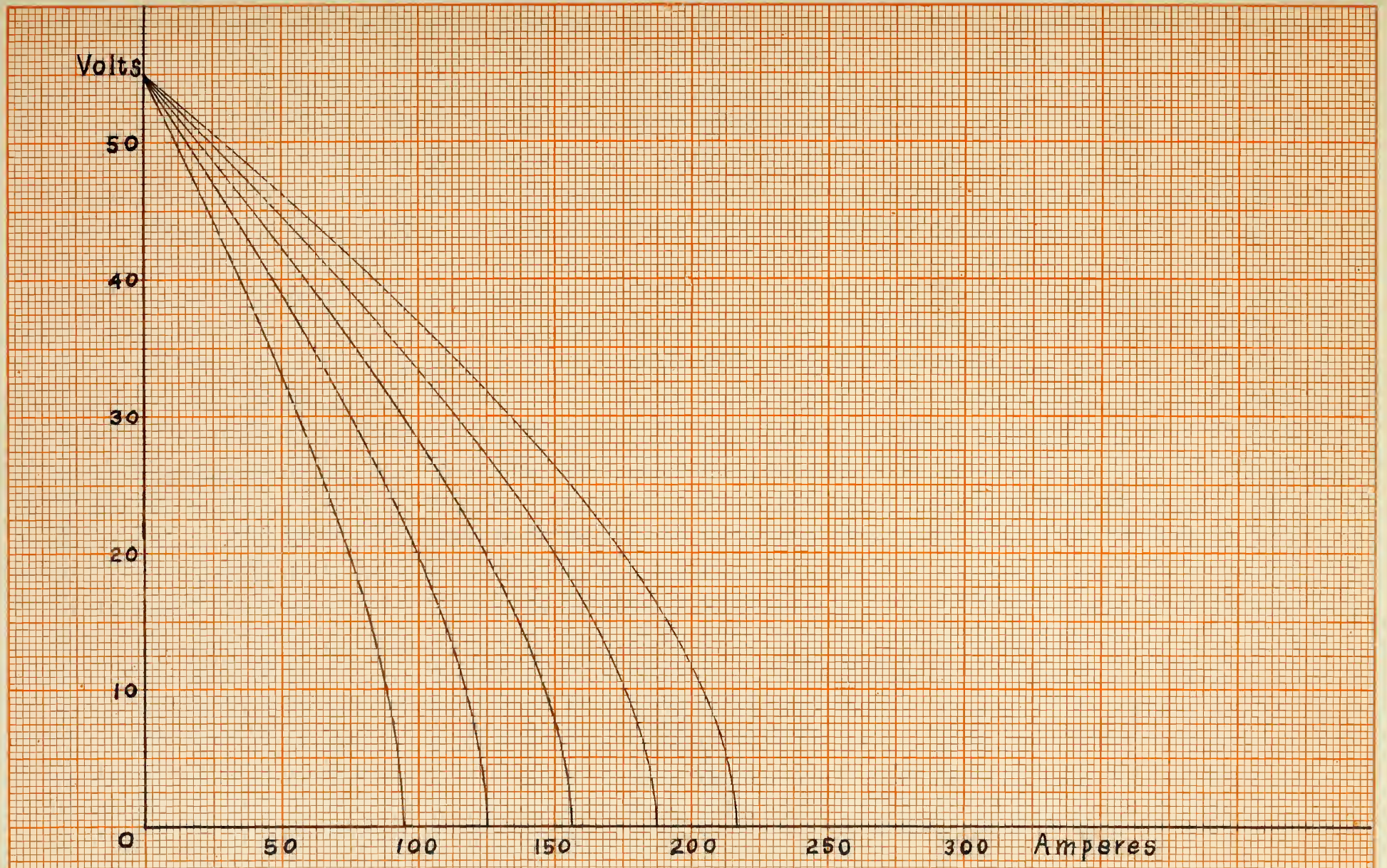

Fig. 7 - Self excited addative compound generator curves. Current adjustment by means of series field strength only.

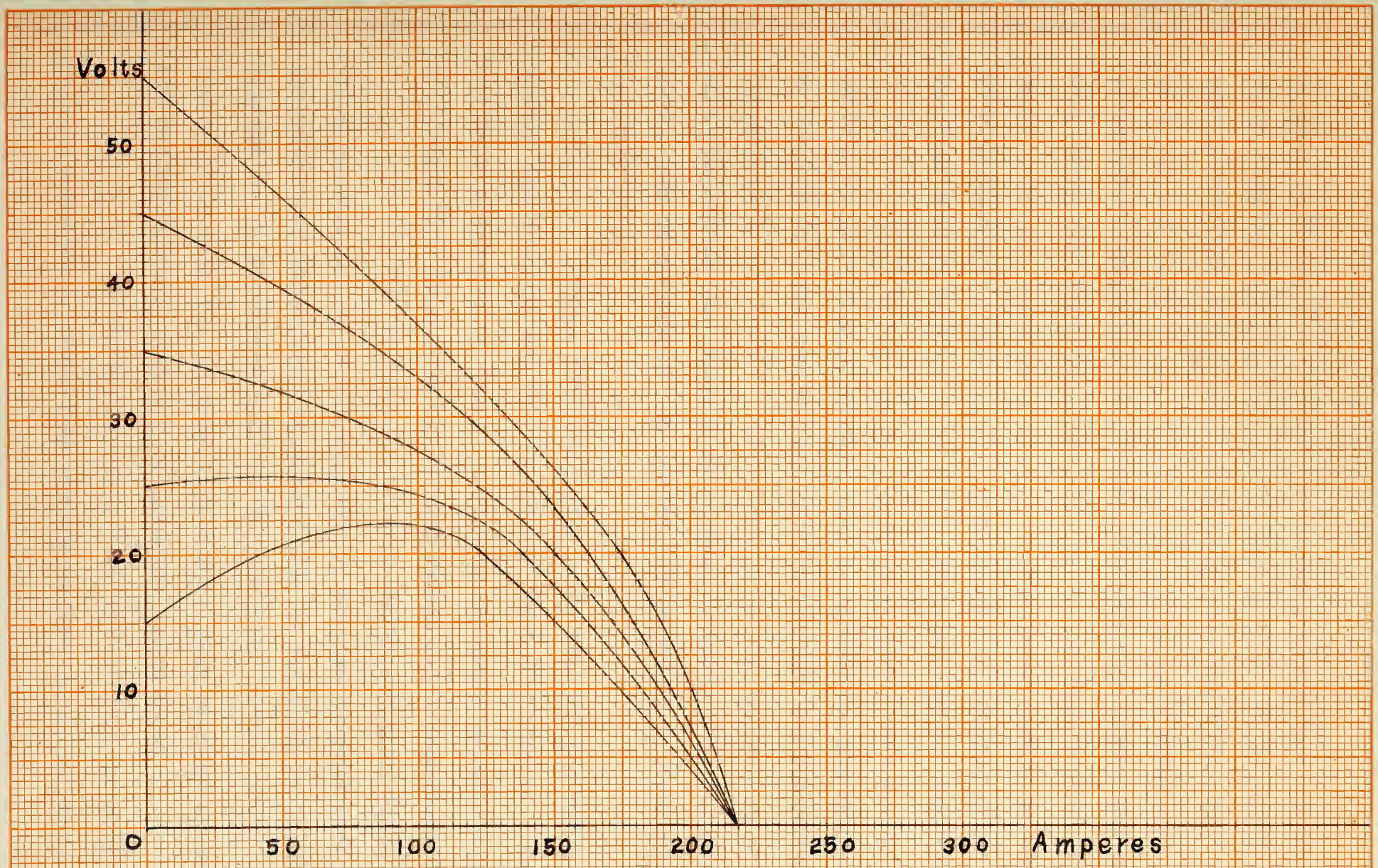

Fig. 8 - Self excited addative compound generator curves. Current adjustment by means of shunt field strength only.

or dial switches, for connecting to the desired tap, or adjustable shunts may be provided for the series field. If it could be easily done the first method would be very satisfactory. However, to bring out taps it is necessary to bring many leads out of each series coil, make many connections inside the frame, and bring several leads out from the generator up to the dial switch on the panel. All of these leads are of large enough cable to carry the welding current. This is a very awkward and costly construction. The last method, however, is not to be recommended. The resistance of the series field is low. The contact resistance of the knife switch, or of the dial switch, used in adjusting the series shunt, is subject to wide variations, and may exceed the resistance of the series field itself. As a result, it is impossible to foretell definitely the percentage current shunted from the series field, and consequently the welding obtained by a given setting is indefinite.

Until very recently, this type of arc welding generator was used by the U.S. Light and Heat Corporation, but it has now been abandoned by them. A diagram of their apparatus is shown in Figure #9. This type is not now being built commercially.

22. Separately Excited Differentially Compound Wound Generators. - In the separately excited differential compound generator the separately excited field is designed to produce the desired no load voltage and the differential series field is designed to reduce the voltage from the no load voltage to the welding voltage without the use of external resistance.

Generators of this type may be made as small as any welding generator, their cost should be very low, and they should

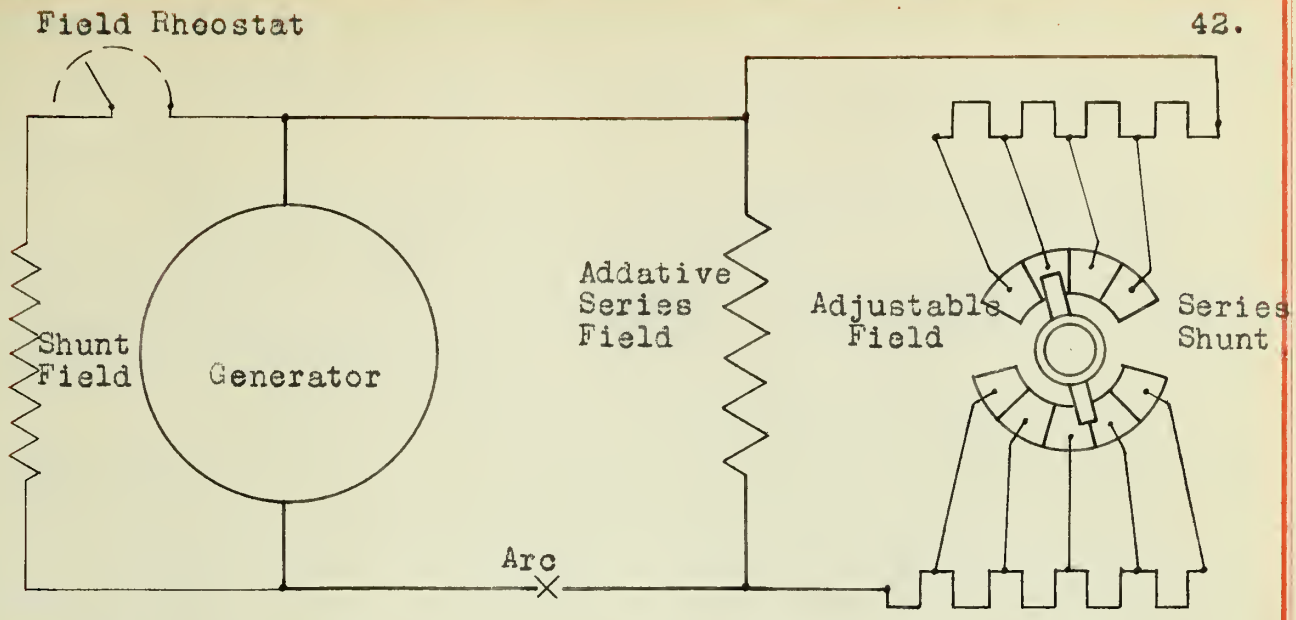

Fig. 9 - Diagram of a self excited addative compound wound generator with an adjustable series field shunt.

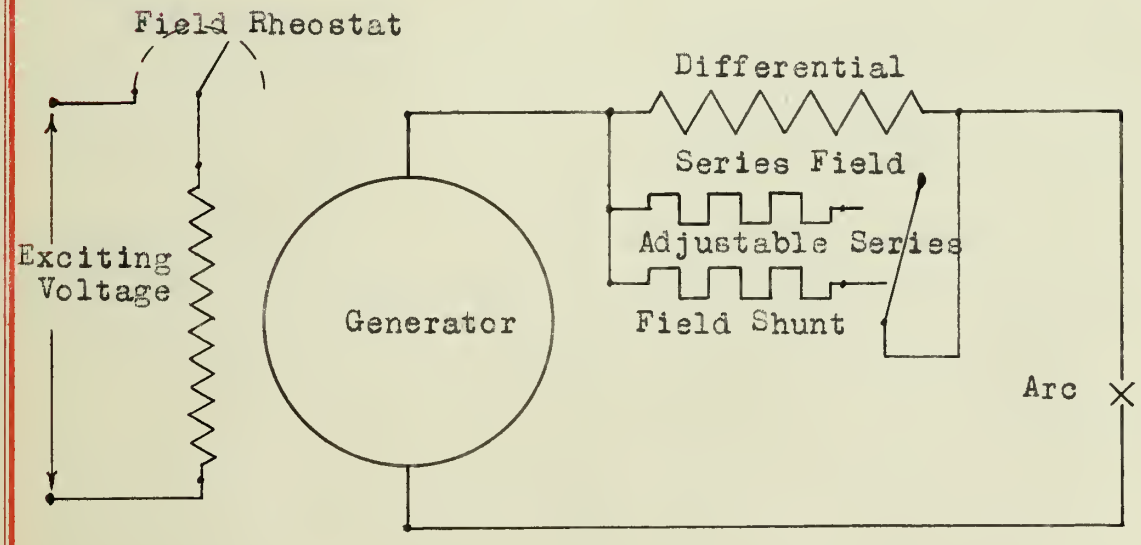

Fig. 10 - Diagram of a separately excited differential compound wound generator with an adjustable series field shunt.

be readily portable. They are simple and have a high electrical efficiency.

Such generators have a wide variation of main pole flux, but their speed of flux change is unexcelled. Therefore they require but little inductance.

Two methods are used in adjusting to produce the desired welding current. The usual method is to obtain approximately the welding current desired by varying the strength of the series field, either by shunts, or taps, and making the finer adjustments with the separately excited field rheostat. Generators of this type are manufactured in this country by the Lincoln Electric Company, and by the C. and C. Electric and Manufacturing Company, and are manufactured in England by the Metropolitan-Vickers Company. A diagram of the Lincoln set is shown in Figure #10. All of these sets use an adjustable shunt on the series field, which, as stated, is objectionable. The volt-ampere curves to be expected are shown in Figure #11, and are very desirable. The auxiliary apparatus required is a voltmeter, an ammeter, a knife switch, a reactor, a rheostat, some means for changing the series field strength, and a separate source of excitation.

The other method of adjusting to get the desired welding current is to adjust the separately excited shunt field only, not changing the series field strength at any time. This scheme is far simpler, and gives approximately the volt-ampere curves shown in Figure #12. It does, however, require considerable field space for the shunt coil, for a large shunt coil must be used. To illustrate, assume that to obtain 35 volts, no load, (which will be taken as a minimum), 1000 ampere turns are required per pole,

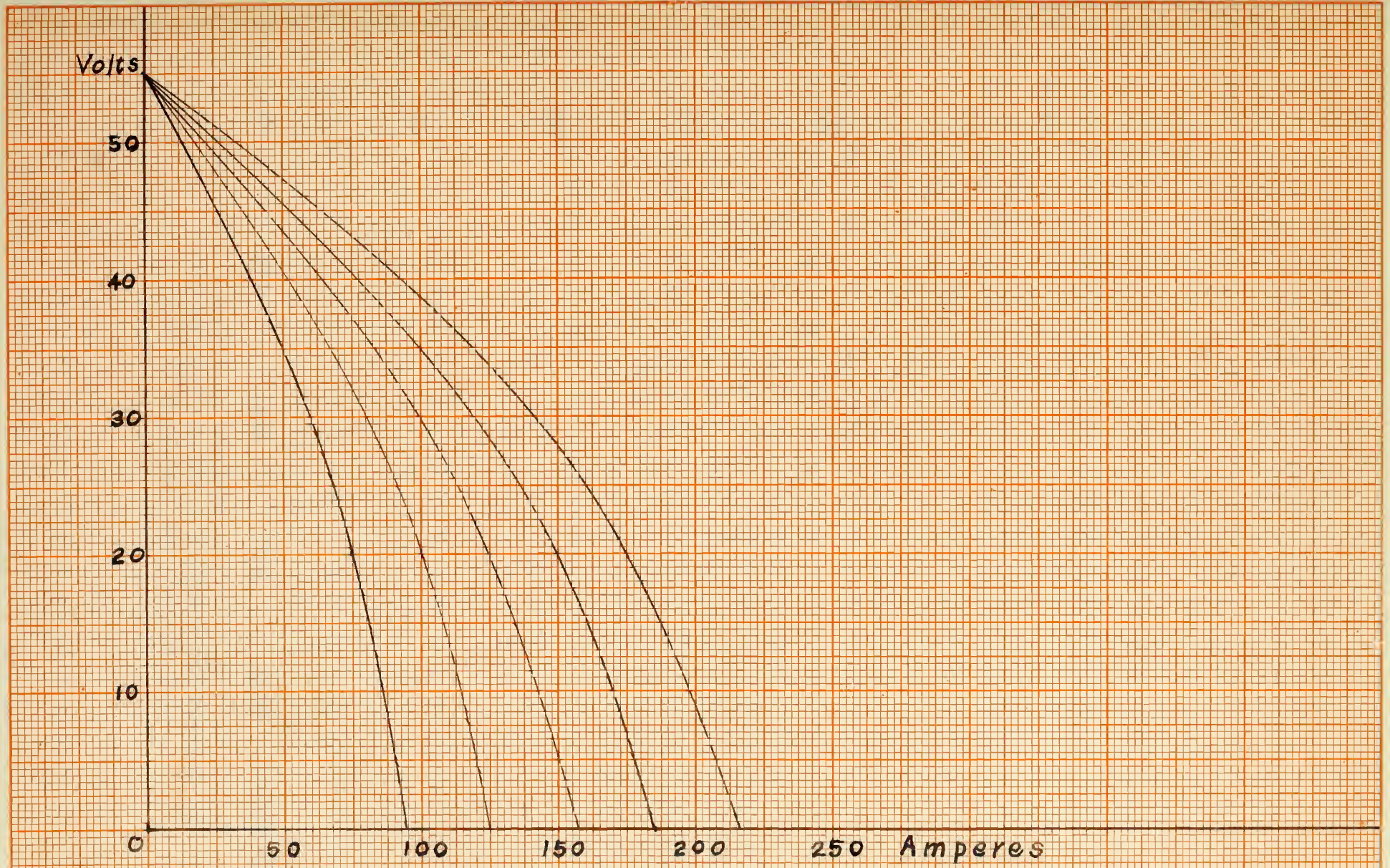

Fig. 11 - Separately excited differential compound generator curves. Current adjustment by means of series field strength only.

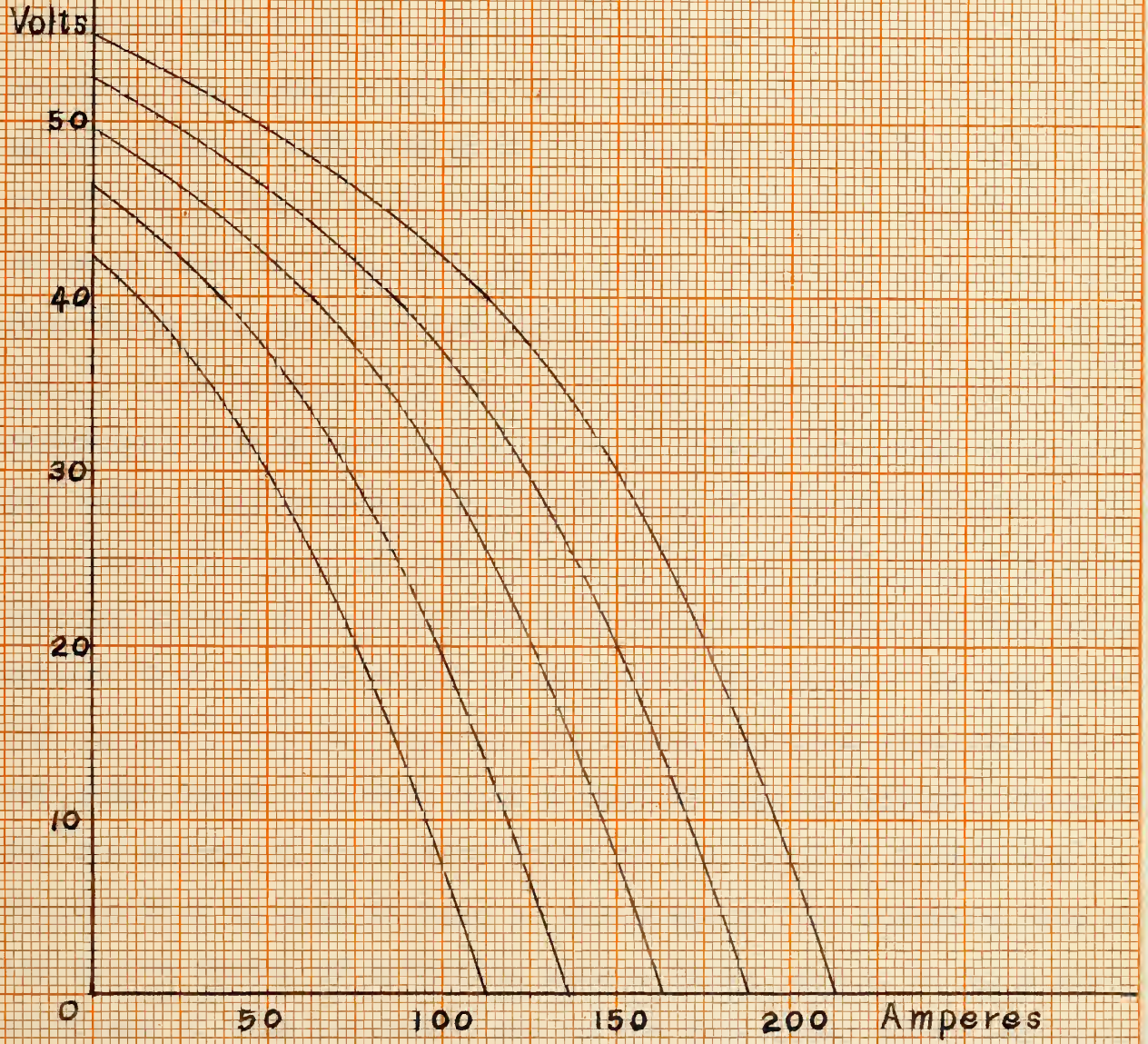

Fig. 12 - Separately excited differential compound generator curves - Current adjustment by means of separate excitation only.

and 1800 are required to obtain 55 volts. Assume that to obtain 75 amperes welding current the difference between the series ampere turns per pole, and the separately excited shunt ampere turns per pole, will be 700 ampere turns, and that, when the current is to be 175 amperes, 1625 ampere turns per pole are required. Then when the first method is used about $\frac{1800 - 700}{75}$ or 15 series turns are required, but at 175 amperes welding the series field is reduced to the strength of one turn and the separately excited field ampere turns is 1800 per pole. If the second method is used the series turns required to obtain 75 amperes with no less than 35 volts no load is $\frac{1000 - 700}{75}$ or 4 turns. This is a minimum. When four turns are used for 175 ampere welding the differential series ampere turns becomes 175 x 4 or 700 ampere turns, and the total separately excited shunt ampere turns become 700 + 1625 or 2325 per pole. This requires more field copper, and more field space than does the first method. The shunt field would have a greater damping action at high current than would the field for the first method, due to the greater cross section of copper. At low welding currents, however, due to the higher external resistance in the shunt field, it would have a smaller damping action. Considering the effect of the series field on the speed of action the first method is seen to have an advantage at low currents, due to its higher number of effective series turns, and to be at a disadvantage at high currents, due to its then lower effective number of series turns. Balancing the damping action against the series effect it seems there is little difference between the speed of action of the two machines.

The diagram for this generator is the same as that of

Figure #10 except that there is no adjustable shunt on the series fields. The auxiliary apparatus required is a voltmeter, an ammeter, a knife switch, a separate source of excitation, a rheostat and a reactor. This type of generator has not been manufactured commercially.

23. Separately Excited Self Excited Shunt Wound Generators. - A generator with a separately excited shunt field and a self excited shunt field can be adjusted to give an ideal arc welding volt-ampere curve. To adjust the welding current either one or two adjustments may be used. A rheostat should be connected in series with the separately excited field, for welding adjustment, and a rheostat may be connected in series with the self excited shunt field. If only one rheostat is used, the type of volt-ampere curves shown in Figure #13 is obtained and if two rheostats are used almost any shape of curves may be produced, depending on the relative adjustments. However, the best type of curves to be obtained are shown in Figure #14. Either set of curves are very desirable.

Considering only its speed of action, the separately excited shunt wound generator is not well suited for welding service. The flux has a wide range of change, and the dependence on a self excited shunt field to cause this change results in a "slow" generator. The larger the percentage that the self excited shunt ampere turns is of the total ampere turns, the slower will be the flux rate of change. A self excited shunt field is, as previously stated, very slow in action. Due to this sluggishness the self excited separately excited generator requires the use of a large amount of inductance if used for welding service.

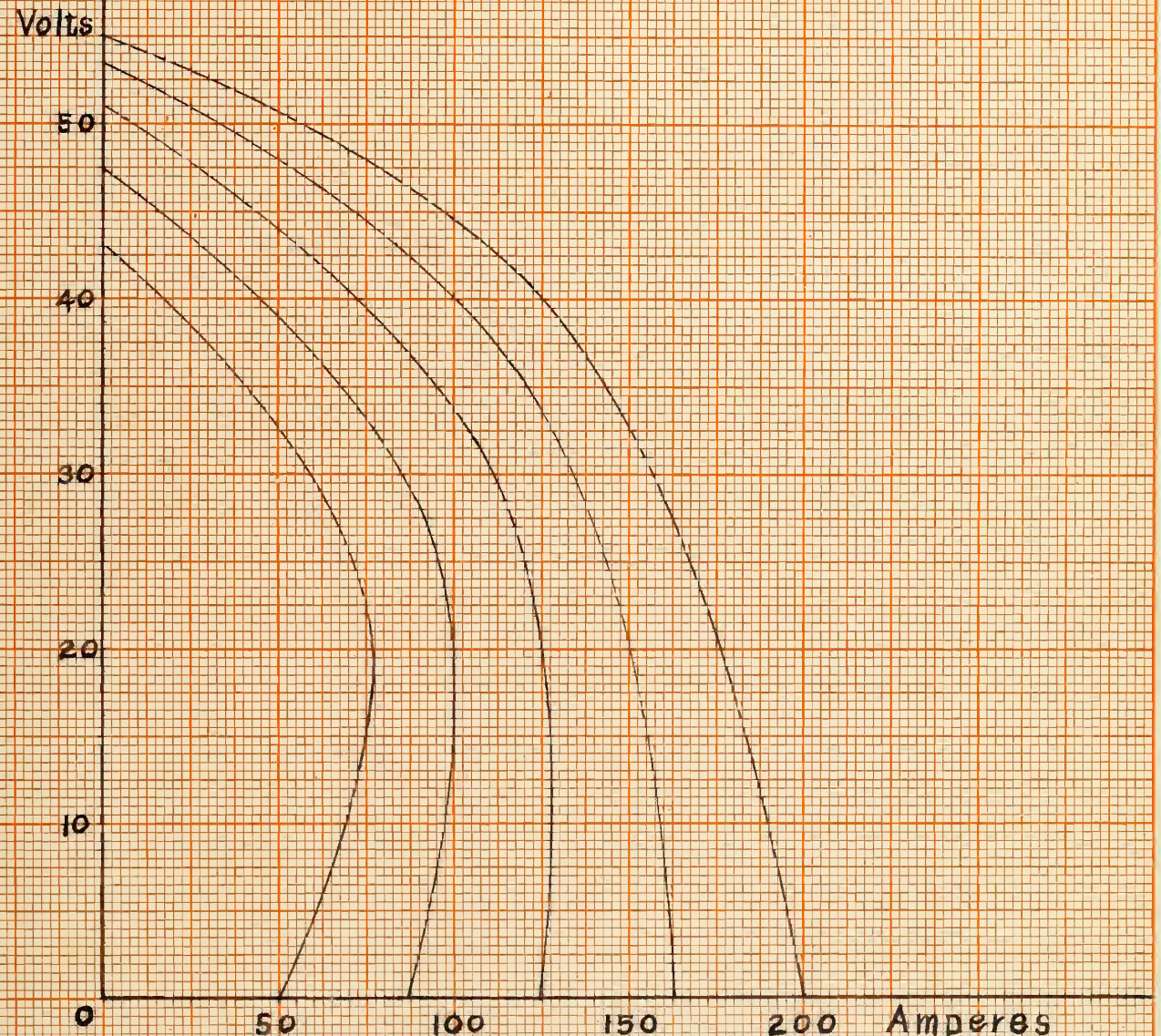

Fig. 13 - Separately excited self excited shunt wound generator curves - Current adjustment by means of separate excitation only.

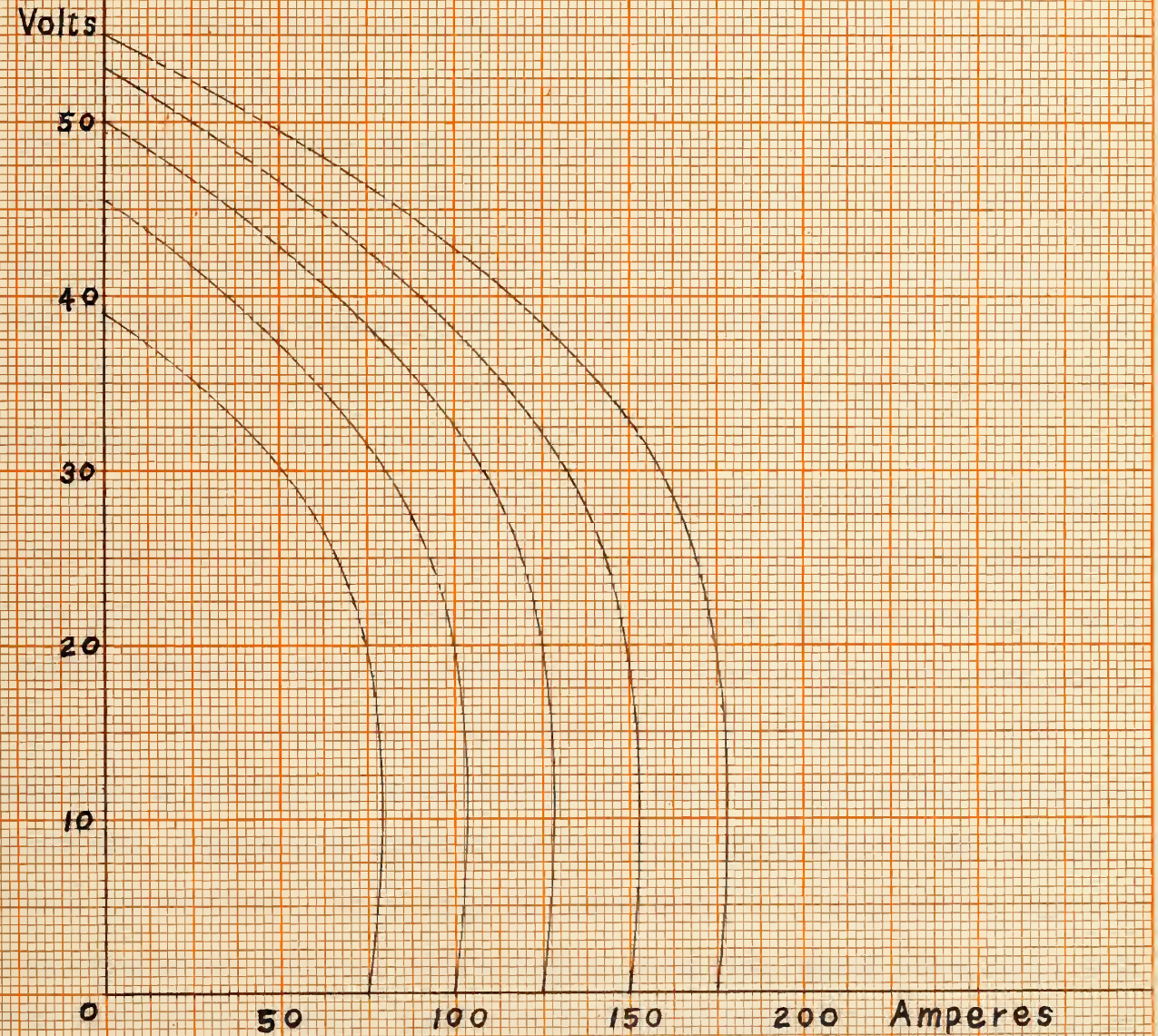

Fig. 14 - Separately excited self excited shunt wound generator curves - Current adjustment by means of both fields.

This type of generator can be made as small as any other generator for the service. It is very simple in construction, but if two rheostats are used the operating adjustments may become complex and the wrong shape of volt-ampere curve is as likely to be produced as is the right one. The cost of such a generator is low, and it is readily portable by truck.

The auxiliary apparatus required for this generator is a voltmeter, an ammeter, a knife switch, one or two rheostats, a reactor and a separate source of excitation. A typical schematic diagram of such a generator, using one rheostat, is shown in Figure #15. A separately excited self excited shunt wound generator is now being manufactured commercially by the U.S. Light and Heat Corporation, and replaces the self excited addative series generator which they formerly built.

24. Separately Excited Self Excited Differential Compound Generators. - The separately excited self excited differential compound wound generator is at present the most favored of all single operator welding generators by manufacturers of such machinery. Such generators may have their welding current controlled by almost any combination of self excited shunt field adjustment, separately excited shunt field adjustment, and series field adjustment. This type of generator is a compromise between the separately excited differential compound wound generator, and the separately excited self excited generator. In size all three are the minimum possible, and all three are readily portable by truck. The generator with three separate fields, however, is less simple, and consequently, slightly more costly.

Its speed of flux change is better than that of the self

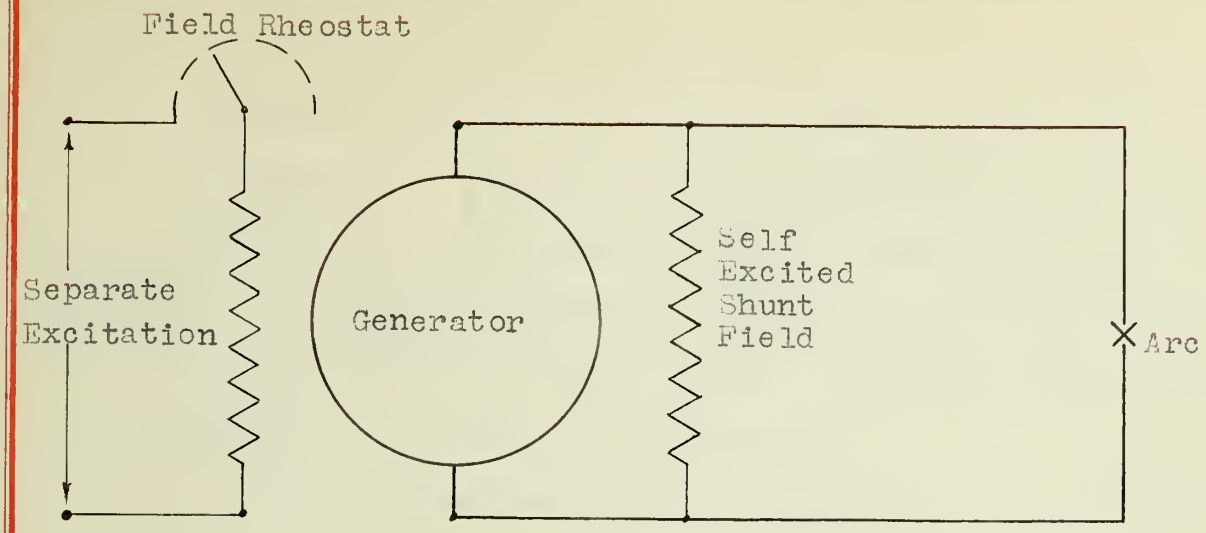

Fig. 15 - Diagram of a separately excited, self excited shunt wound generator, with one field adjustment.

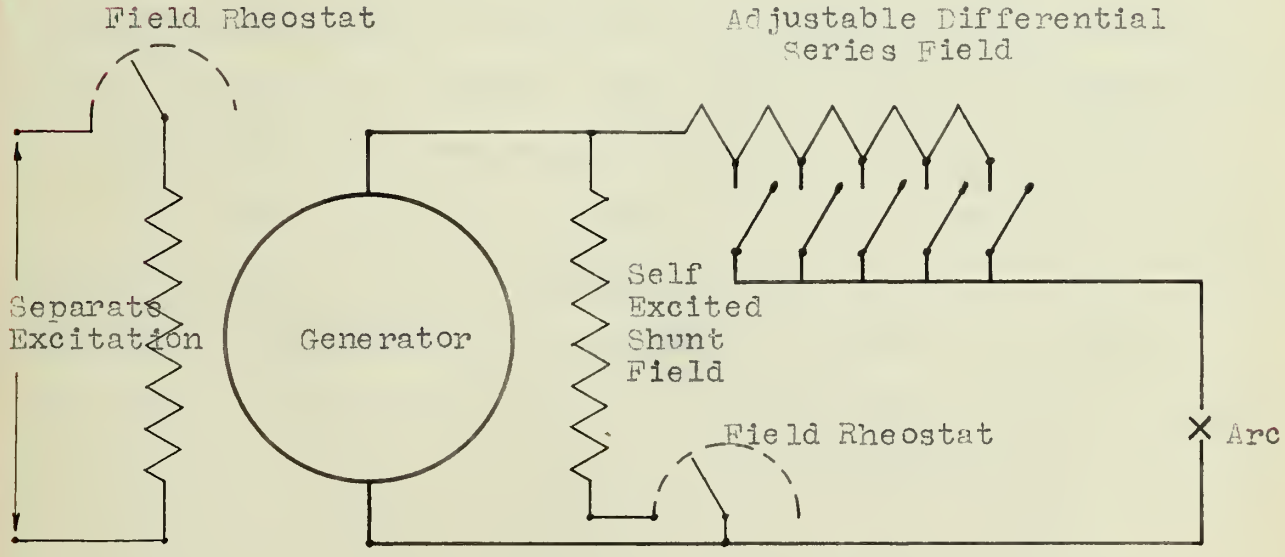

Fig. 16 - Diagram of a separately excited, self excited differential compound wound generator, with all fields adjustable.

excited separately excited generator, but is not so good as that of the separately excited differential compound generator. The relative strength of the three fields determines which it most nearly approaches. The weaker the self excited field, and the stronger the separately excited and the differential series fields the faster is the rate of flux change. The inductance required is dependent on the speed of flux change.

The auxiliary apparatus required by this generator is a voltmeter, an ammeter, a knife switch, one or two rheostats, a source of separate excitation, possibly some means of adjusting the series field, and a reactor. A diagram showing this generator and the maximum of auxiliary apparatus (except meters, reactor, and knife switch) is shown in Figure #16.

When adjustment is made only of the separately excited field the volt-ampere curves would be about as shown in Figure #17. These are desirable curves. The curves at the low welding currents are less desirable than those of the high welding currents.

When adjustment is made of the self excited field only, the volt-ampere curves produced are approximately as shown in Figure #18. These curves are acceptable, although the tendency is for the no load voltage to be too low when the rheostat is set for low welding currents, and for the short circuit current to be too low when the rheostat is set for high welding currents.

When rheostats are put in series with both the separately excited field and the self excited field, many different shapes of volt ampere curves may be obtained. When adjusting for a given welding current the double adjustment permits the operator to obtain either good or bad volt-ampere curves. At their best the

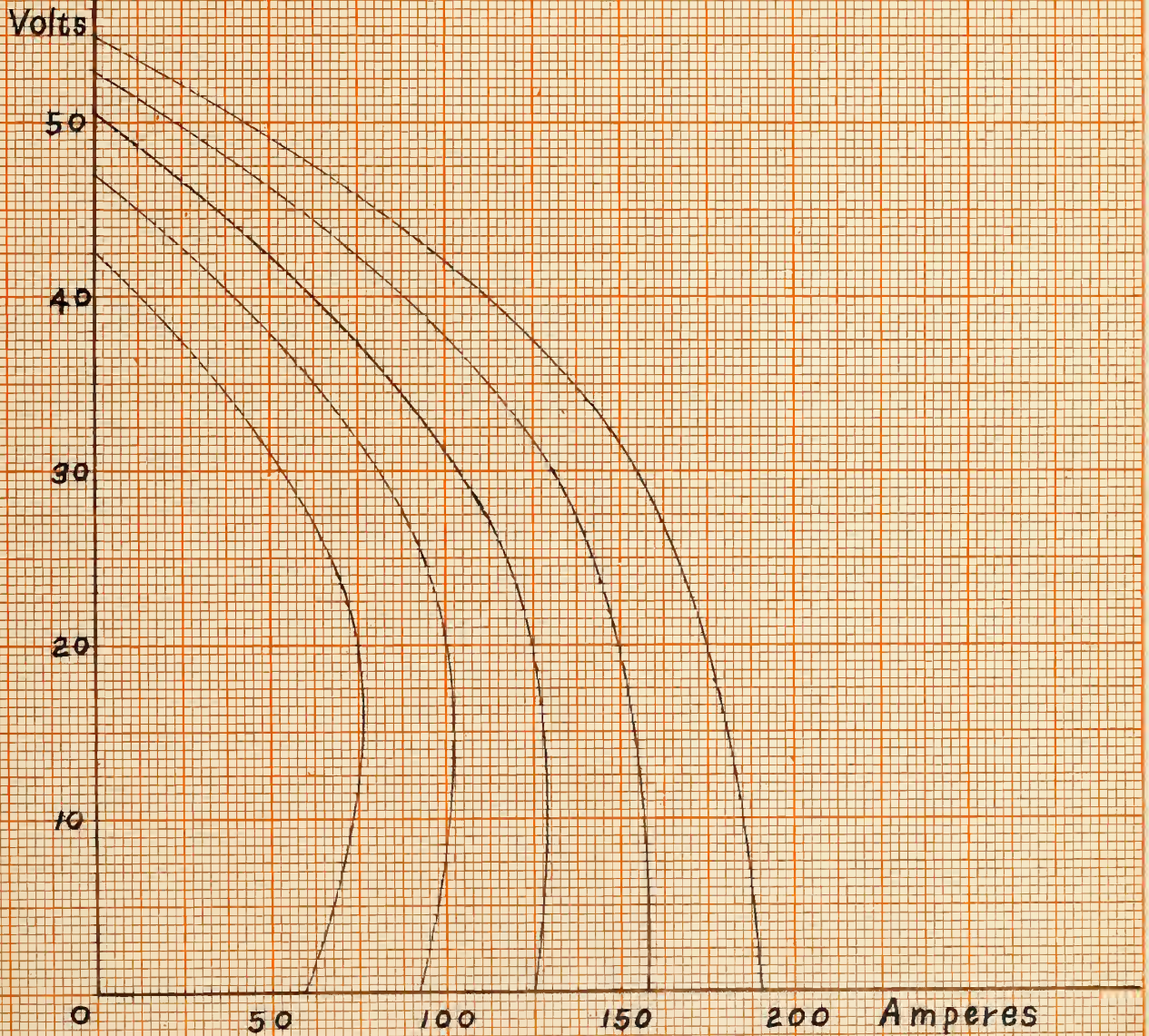

Fig. 17 - Separately excited, self excited, differential compound wound generator curves - Current adjustment by means of separate field strength only.

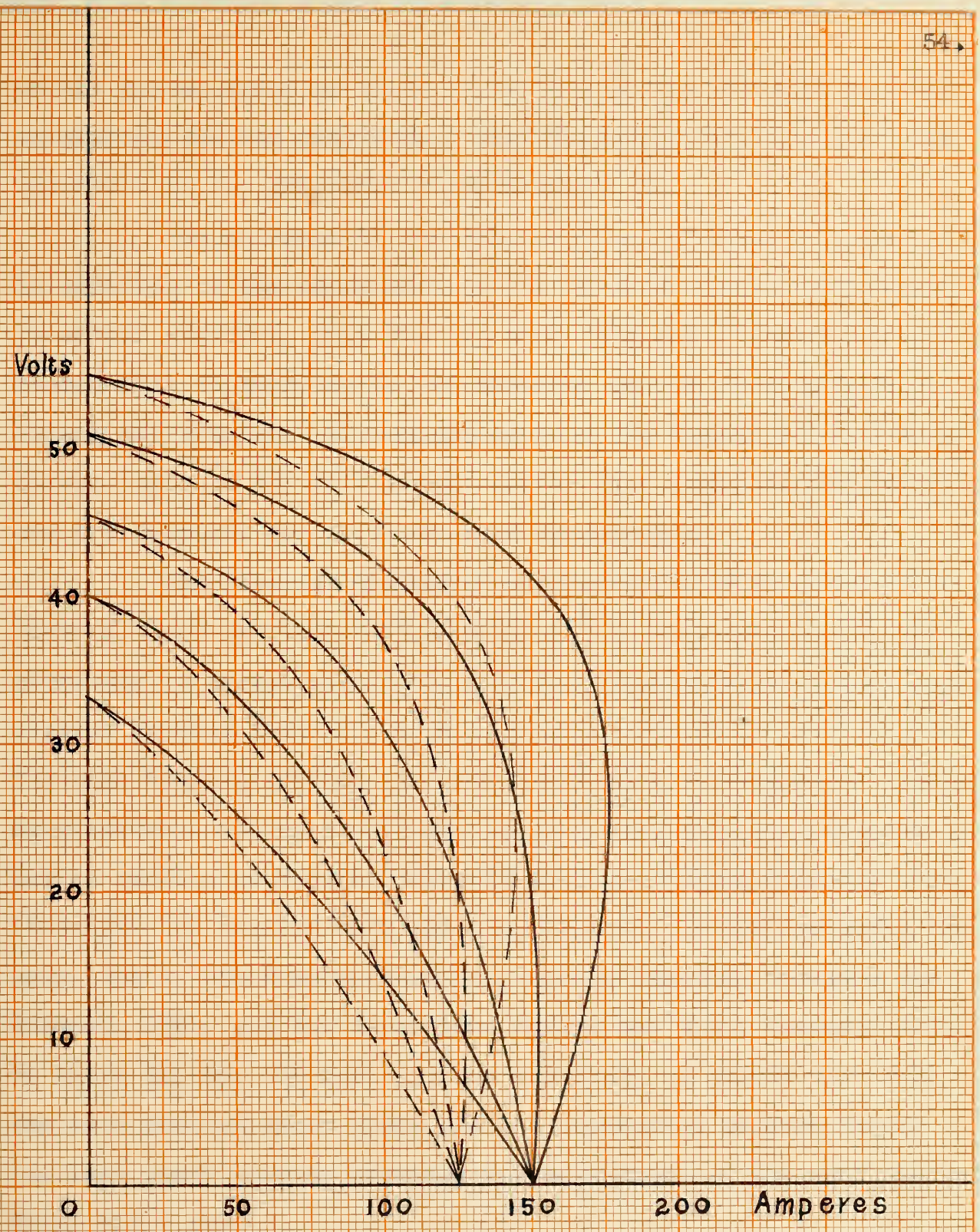

Fig. 18 - Separately excited self excited, differential compound wound generator curves - solid lines - current adjustment by means of self excited field only - broken lines - same, except series field strengthened.

curves appear about as shown in Figure #14 for the self excited separately excited generator. Such double adjustments make the operation of the generator complicated.

The strength of the series field might also be adjusted in addition to the adjustment of one or both of the other fields. In actual practice, this has not been done commercially for the reason that it complicates the control, and is not necessary to obtain satisfactory volt-ampere curves. In Figure #18 the dotted curves indicate the volt-ampere curves that would be obtained if the differential series field were strengthened.

The American companies manufacturing plain separately excited, self excited, differential series generators both use rheostats in series with both the self excited shunt and the separately excited fields. These companies are the Siemund Wenzel Electric Welding Company, and the Burke Electric Company. English manufacturers making separately excited self excited differential series welding generators are Metropolitan-Vickers Company, Ltd., (Formerly the British Westinghouse Electric and Manufacturing Company, Ltd.), the Premier Electric Welding Company, Crompton and Company, Ltd., and the Lancashire Dynamo and Motor Company, Ltd. Of these all but the last one use rheostats in series with both the self excited shunt field and the separately excited field. The last named however provides for adjustment of the self excited shunt field only.

25. Interconnected Generators. - When generators requiring separate excitation are used, it is possible to interconnect the exciter circuit and the welding circuit in such a way that the exciter voltage is impressed, through a resistance, on

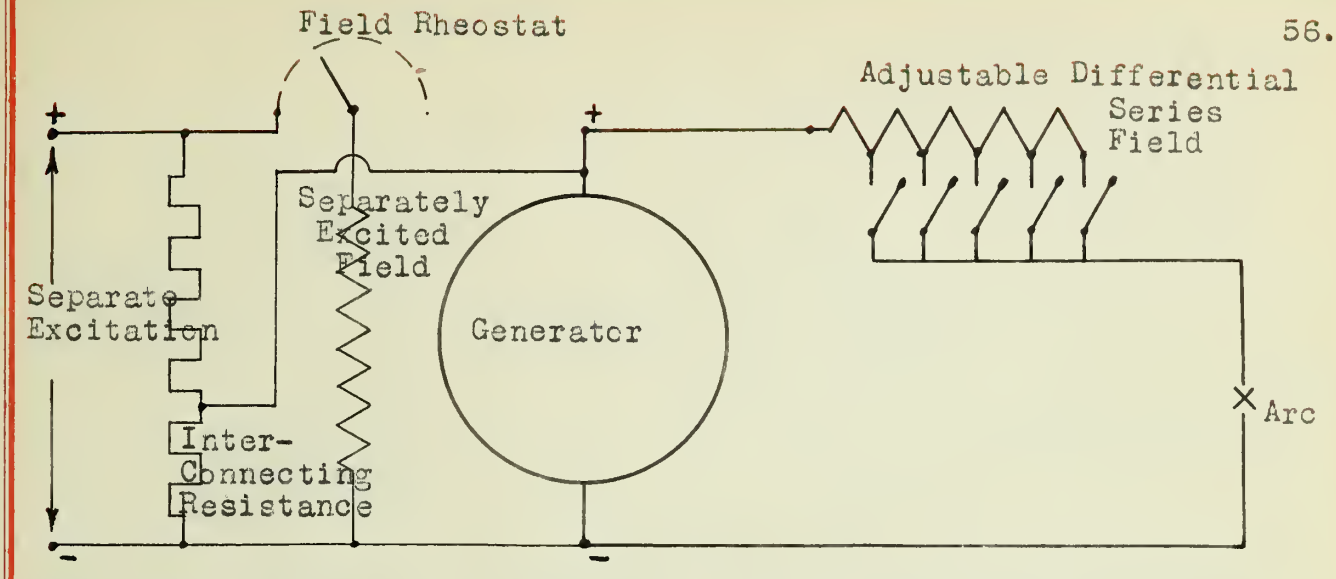

Fig. 19 - Diagram of a separately excited differential compound wound inter-connected generator with both fields adjustable.

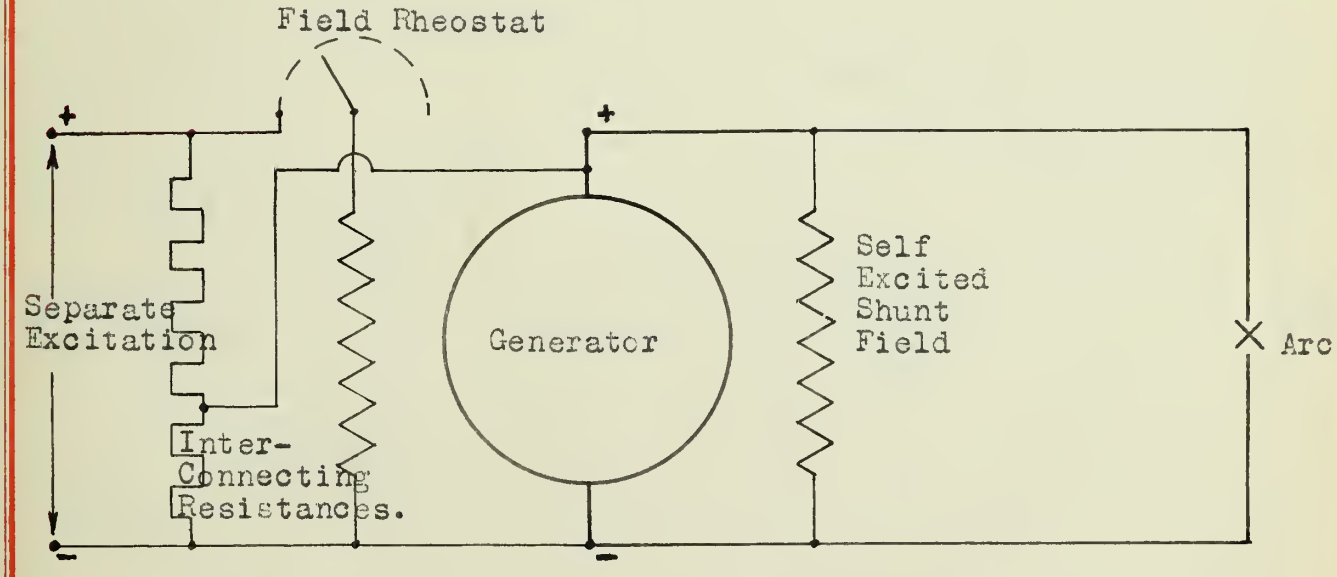

Fig. 20 - Diagram of a separately excited, self excited shunt wound inter-connected generator with adjustment of the separate field only.

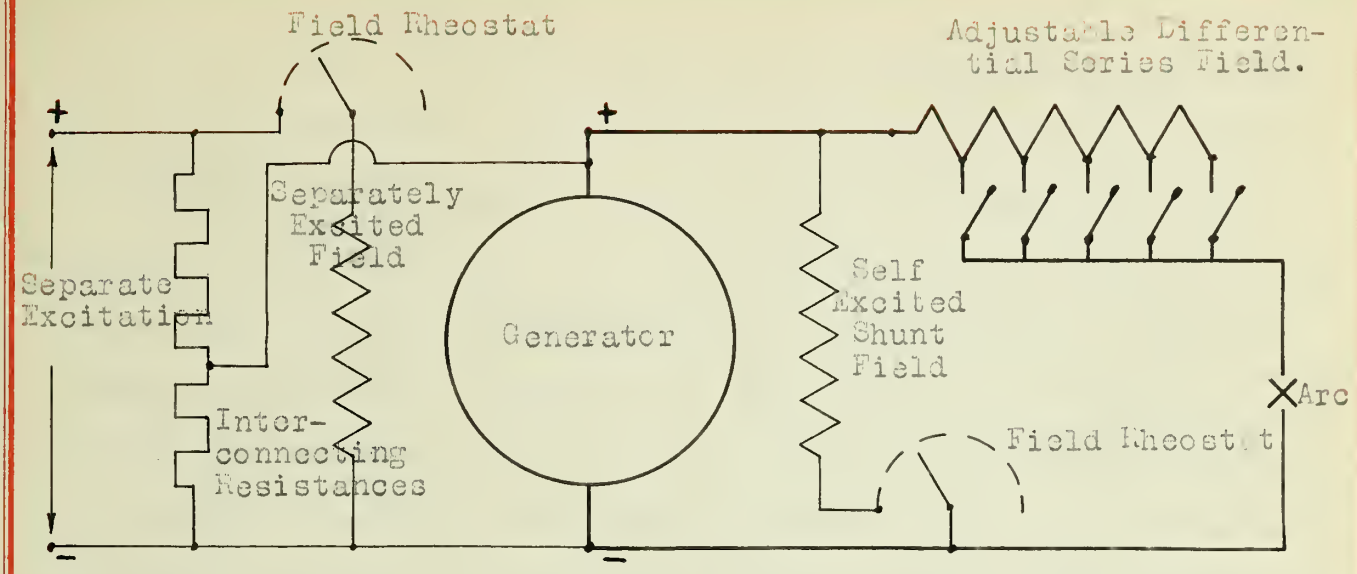

Fig. 21 - Diagram of a separately excited, self excited differential compound wound interconnected generator, with all fields adjustable.

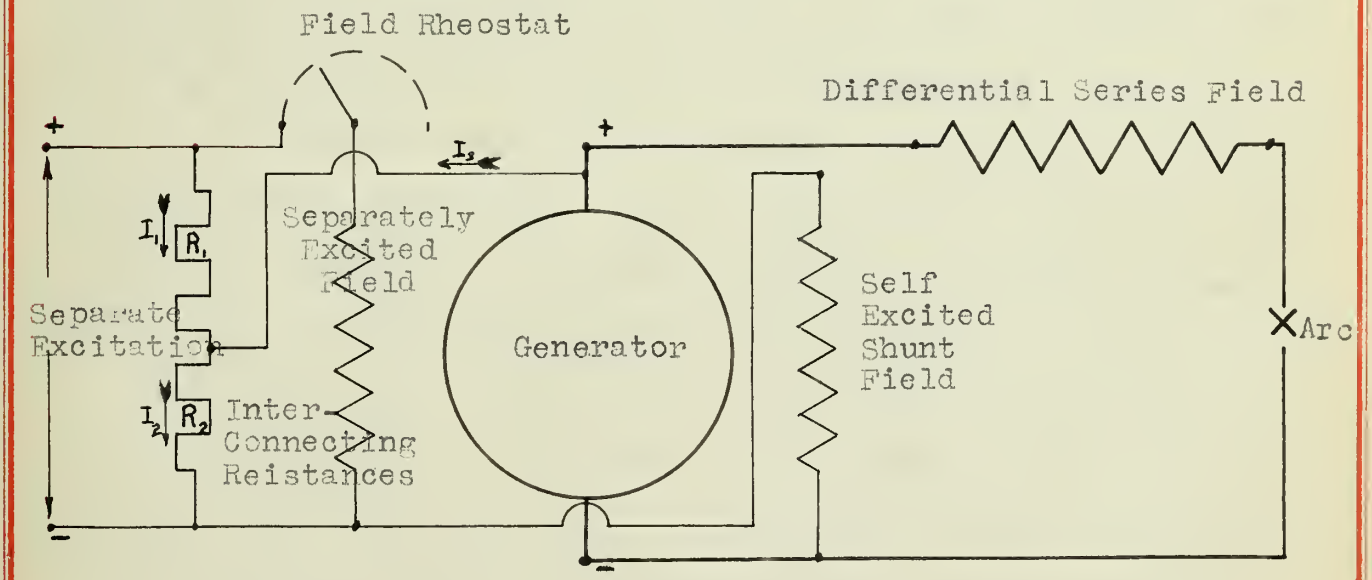

Fig. 22 - Diagram of a special type of separately excited, self excited differential compound wound interconnected generator, with the separately excited field only adjustable.

the arc. Figures #19, #20, and #21 show diagrams of simple interconnected generators. These generators are, then, consequently a compromise between the generator before interconnection, and a plain resistance welder, discussed in Section 19. Since the current taken from the exciter circuit is usually small, the volt-ampere curves are not materially affected by interconnection. Since the resistance welder has an instantaneous voltage response to changes of current, the interconnection would make the arc a little more stable and tenacious than it would be without the interconnection. Such interconnection does not affect the generator size. It does however require a larger exciter than would otherwise be needed; requires that an extra resistance be used in the auxiliary apparatus; decreases the electrical efficiency, due to the loss in the resistance; and makes the set as a whole more complicated, more expensive to build, and harder to repair. None of these three types are being built commercially.

A special type of interconnected generator is shown in the diagram of Figure #22. This is essentially a separately excited, self excited, differential compound, interconnected generator, and its volt-ampere curves would be similar to those shown in Figure #17. Due to its very peculiar connections an analysis of this generator is of interest. If resistances R_1 and R_2 are taken as shown in Figure #22, the resistance of the self excited field, sometimes called the reversing field, is R_3, the exciter voltage is E, and is constant, while the welding generator voltage is E_2, and currents I_1, I_2 and I_3 are assumed as shown in the diagram, then:

$$E_1 = I_1 R_1 + I_2 R_2$$

$$E_2 = I_2 R_2 + I_3 R_3$$

$$I_1 + I_3 = I_2$$

$$E_1 = I_2 R_1 - I_3 R_1 + I_2 R_2$$

$$E_2 = I_2 R_2 + I_3 R_3$$

$$E_1 = (R_1 + R_2) I_2 - I_3 R_1$$

$$E_2 = I_2 R_2 + I_3 R_3$$

$$R_2 E_1 = R_2 (R_1 + R_2) I_2 - I_3 R_1 R_2$$

$$(R_1 + R_2) E_2 = R_2 (R_1 + R_2) I_2 + (R_1 + R_2) R_3 I_3$$

$$(R_1 + R_2) E_2 - R_2 E_1 = I_3 R_1 R_2 + (R_1 + R_2) R_3 I_3$$

$$I_3 = \frac{(R_1 + R_2) E_2 - R_2 E_1}{R_1 R_2 + (R_1 + R_2) R_3}$$

$$= \frac{(R_1 + R_2) E_2 - R_2 E_1}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

All of the resistances are constants. Then let

$$\frac{R_1 + R_2}{R_1 R_2 + R_1 R_3 + R_2 R_3} = C_1 \text{ and } \frac{R_2}{R_1 R_2 + R_1 R_3 + R_2 R_3} = C_2$$

Then $I_3 = C_1 E_2 - C_2 E_1$

If the effective turns per pole of the self excited field is T_1, then the self excited field ampere turns per pole becomes $C_1 E_2 T_1 - C_2 E_1 T_1$. Assume the separately excited field has an ampere turns per pole of $C_3 E_1 T_1$. Then the total ampere turns per pole due to the two fields is equal to $C_1 E_2 T_1 -$

$C_2 E_1 T_1 + C_3 E_1 T_1 = (C_3 + C_2) E_1 T_1 + C_1 E_2 T_1$. Exactly the same ampere turns per pole could have been obtained by using a separately excited field of the constant ampere turns $(C_3 - C_2) E_1 T_1$ and a self excited shunt field with $C_1 E_2 T_1$ ampere turns per pole, and using connections as shown in Figure #21.

As compared to the generator whose diagram of connections is shown in Figure #21, the volt-ampere curves are the same. The speed of action of the generator of Figure #22 is probably superior, for it has a comparatively high resistance in series with the self excited shunt coil, which tends to reduce the damping action of that coil. Consequently less inductance would be required. This resistance, however, causes an extra loss that lowers the generator efficiency slightly, also this extra resistance R_2 increases the cost of the apparatus slightly and makes it slightly more difficult to assemble and repair. The size and portability is not affected. This type of generator is at present manufactured by the Westinghouse Electric and Manufacturing Company.

A very similar type of interconnected generator is shown in the diagram in Figure #23. It will produce exactly the same volt-ampere curves if proper adjustments are made as will the generator last discussed.

Using the terms R_1 and R_2 for the resistances, with a given setting of the three point rheostat, as shown in Figure #23, R_3 for the combined resistance of the shunt field and its rheostat, as used, I_1, I_2, and I_3 for the currents through these resistances, E_1 for the constant exciter voltage and E_2 for the welding generator voltage, then

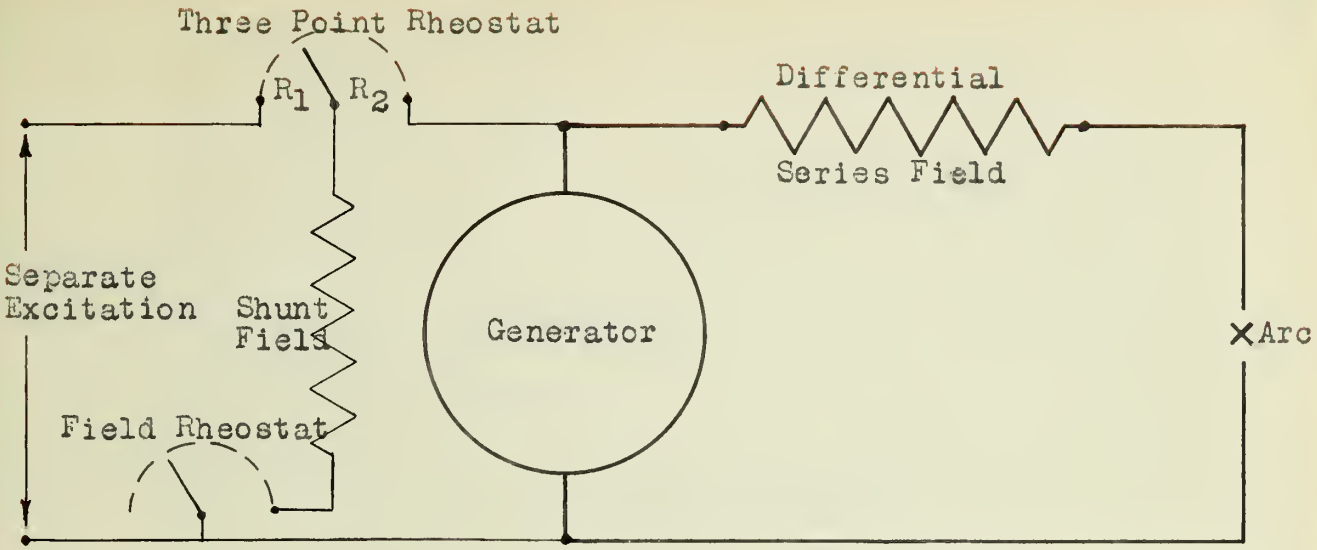

Fig. 23 - Diagram of a special type of separately excited self excited differential compound wound interconnected generator with both shunt fields adjustable.

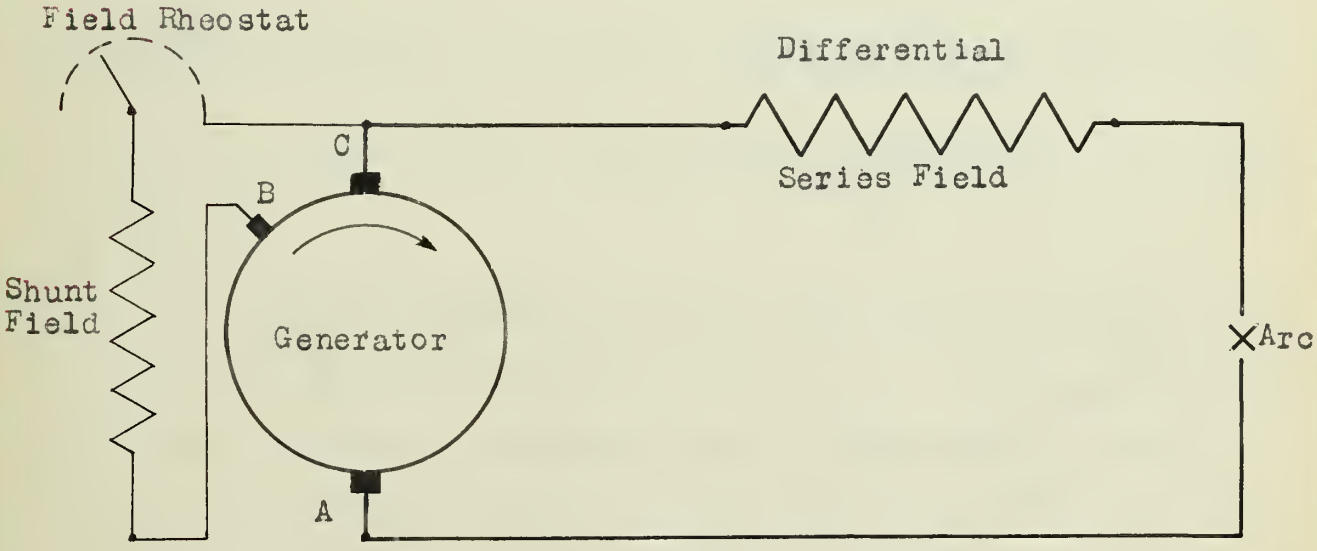

Fig. 24 - Diagram of a self excited differential compound wound third brush generator with shunt field only adjustable.

$$E_1 = I_1 R_1 + I_3 R_3$$

$$E_2 = I_3 R_3 - I_2 R_2$$

$$I_1 = I_2 + I_3$$

$$E_1 = I_2 R_1 + I_3 R_1 + I_3 R_3$$

$$E_2 = I_3 R_3 + I_2 R_2$$

$$E_1 R_2 = R_1 R_2 I_2 + (R_1 R_2 + R_2 R_3) I_3$$

$$E_2 R_1 = R_1 R_2 I_2 + R_1 R_3 I_3$$

$$E_1 R_2 + E_2 R_1 = (R_1 R_2 + R_2 R_3 + R_1 R_3) I_3$$

$$I_3 = \frac{E_1 R_2 + E_2 R_1}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

If in this case T_1 is the number of effective turns per pole of the shunt field, $(C_3 - C_2)$ be allowed to equal $\frac{R_2}{R_1 R_2 + R_1 R_3 + R_2 R_3}$, and C_1 to be $\frac{R_1}{R_1 R_2 + R_1 R_3 + R_2 R_3}$, then the effective shunt ampere turns per pole becomes $(C_3 - C_2) E_1 T_1 + C_1 E_2 T_1$.

This is exactly the same formula as was obtained for the last interconnected generator discussed. It indicates that if the fields are properly designed, and the adjustments properly made, the total ampere turns per pole due to shunt fields, separately excited and self excited, would be exactly the same on either machine when both have the same generator voltage. With proper adjustments, then, the same volt-ampere curves should be obtained. The three point rheostat is adjusted primarily to obtain the saturation curve shape desired. It changes the relative

strength of the separately excited, and of the self excited, action of the shunt field. This rheostat could be eliminated and R_1 and R_2 left as constant, instead of adjustable, resistances. This would give the operator less control, and would probably insure the use of better volt-ampere curves than would be otherwise used.

The field rheostat is adjusted primarily to control the magnitude of the welding current.

This type of interconnected generator gives the same volt-ampere curves as does the interconnected generator last described; it has the same speed of action, the same efficiency, the same inductance and is the same size. However this generator itself is slightly more simple in construction, as it has only one set of shunt field coils instead of two. Therefore the generator would be slightly cheaper, and easier to repair. This type of generator is not at present being manufactured commercially.

26. Self Excited, Differential Series, Third Brush Generator. - A review of the types of single operator welding generators discussed will show that every generator that was entirely self excited either had a very low efficiency or a very slow speed of flux change. All the generators considered were ordinary generators except for specially designed field windings. An exciter necessarily adds complication to a set and makes it more expensive. Many schemes have been suggested for an entirely self excited welding generator that would have no undesirable welding characteristics, but every such scheme required a very special type of generator construction.

One of the generators suggested is the self excited

differential series third brush generator whose diagram is shown in Figure #24. The construction of this generator is much the same as used for third brush automobile battery charging generators. However a differential series field is added and the shunt field is connected between brushes B and C instead of A and B.

If a generator is saturated magnetically at no load both the pole tips are then usually saturated. If load is thrown on the generator the armature ampere turns tend to saturate further the trailing pole tips. Even with no field excitation, the trailing pole tip will be saturated if a very large current is flowing. In Figure #25 is shown the voltage that would be induced in a conductor of the rotating armature at no load and at short circuit. It is assumed that there is a slight excitation at short circuit and that therefore some current is flowing. The brushes A, B, and C shown indicate the setting of the brushes. The total induced voltage from B to C is proportional to the area shown under the voltage curve between these two points. It is evident, then, that if the voltage drops due to load, the trailing pole tip remains saturated, and the voltage between brush B and brush C remains approximately constant. This voltage can be used to replace the separate exciter, and volt-ampere curves approximately as shown in Figure #12 would be obtained.

If the brush B is shifted toward brush A it will be noted that voltage B-C will increase at no load, but that it will decrease, instead of remaining constant, when the load comes on, and that the amount of this decrease depends on the position of the brush B. It can be set to get any percentage decrease that is desired from approximately none to approximately 100% decrease.

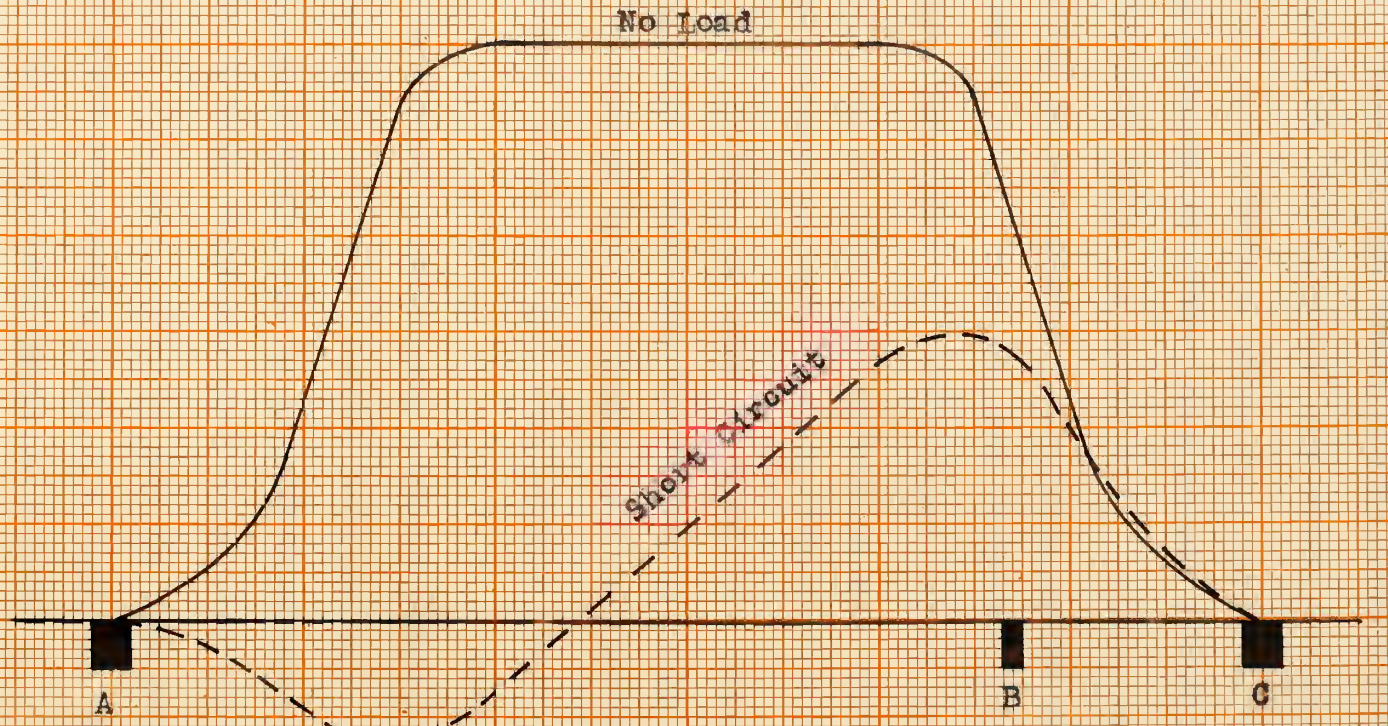

Fig. 25 - Generator field forms.

Then the setting of brush B will determine not only the excitation voltage but also the degree in which the generator will act like a separately excited, or like a self excited, generator.

It should be noted that, in order to obtain a high inductance, the pole tip should never be saturated. Therefore actually the peak of the voltage curve will probably be higher at short circuit with full load current, than it will be at no load. This can be compensated for by the setting of brush B.

The welding current is controlled by means of a rheostat in the shunt field. The brush B should be set in position and not moved.

Such a generator has the size, portability, efficiency, volt-ampere curves, and speed of flux action of the corresponding separately excited generator, not interconnected. It requires the same auxiliary equipment as does the separately excited differential series generator, except that the exciter is omitted. Its field windings are as simple as those of the separately excited differential series generator. It requires, however, a rather complicated brush rigging, and the brush B at times short circuits bars between which there is a difference of potential of approximately three volts. This tends to cause sparking under brush B, but this tendency can be made small by using high resistance, and very narrow, brushes. As brush B takes only excitation current from the armature there is, practically, no reactance voltage to overcome, and a very narrow brush can be used. This type of generator is not being manufactured commercially.

27. Self Excited Differential Series Split Pole Generator. - One of the schemes for obtaining a single operator

welding generator which not only has desirable welding characteristics, but which also does not require an exciter, is the use of a self excited differential series split pole generator. Such a generator is shown in Figure #26. The generator has a four pole stator, and a two pole rotor. The welding current is taken from brushes A and C, and the excitation current from A and B. Poles 2 and 4 with brushes A and B constitute a two pole constant potential shunt wound generator. The position of brushes A and C is such that the armature reaction, due to the welding current, will tend to increase the flux in poles 2 and 4. This however can be done in only a very slight degree, as these poles are notched and kept saturated. The poles are proportioned so that the voltage between brushes A and B is approximately thirty volts. The poles 1 and 3 are unsaturated. They have a shunt winding that is, in effect, separately excited, as constant excitation is furnished by the voltage between brushes A and B. They also have an adjustable differential series winding. Furthermore, the armature reaction due to the welding currents is such as to tend to reduce the flux in poles 1 and 3, and so the armature itself acts on the flux of poles 1 and 3 in the same way as would a differential series field with a constant number of turns. The shunt field and the poles are designed to produce 30 volts at no load. Then at no load the voltage between brushes A and B is 30 volts, between B and C is 30 volts, and between A and C is 60 volts. As load comes on the armature and the differential series ampere turns overbalance the shunt ampere turns, till, at short circuit, the voltage induced by poles 1 and 3 is approximately 30 volts in the opposite direction from what it was at no load. The voltage be-

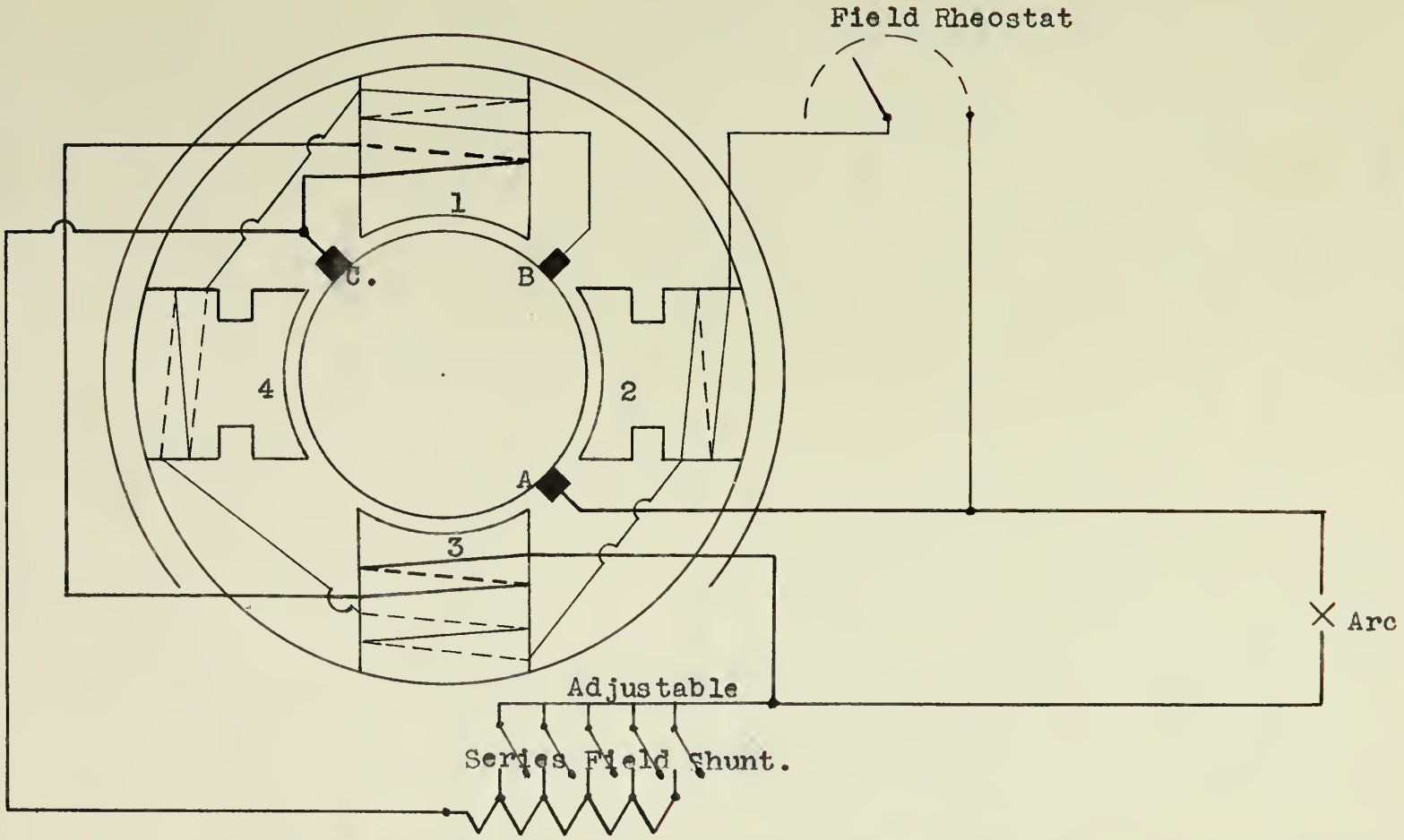

Fig. 26 - Diagram of a self excited differential compound split pole generator with both fields adjustable.

tween brushes A and B then will be 30 volts, the voltage between B and C will be approximately 30 volts in the opposite direction. Then at short circuit the net volts induced between brushes A and C is approximately zero. If the magnetic circuit through poles 1 and 3 is unsaturated, then the volt ampere curves would be approximately as shown in Figure #27, and appear as straight lines. If, however, the magnetic circuit through poles 1 and 3 is saturated at no load, a curve such as is shown in Figure #28 is produced. Either curve is satisfactory for welding purposes.

The control of the welding current is obtained principally by adjusting the strength of the series field. When the approximate welding current desired is obtained, then the shunt field strength is adjusted to give the current desired.

The speed of flux change of such a generator is very rapid. Its speed of flux change is the same as is that of a separately excited differential series generator. Consequently little inductance is required.

This type of generator is nearly as efficient as any other type. The two pole armature is less efficient than the four pole and so slightly decreases the generators efficiency.

Such a generator will be larger, and consequently more costly and less portable, than the standard generator. A two pole armature has longer end connections than does a four pole armature, and so has a greater loss there. Its ventiliation is usually poorer, and so it can dissipate less loss. As a result of these two factors, a two pole armature is larger than a four pole one of the same rating. Also, if part of the magnetic circuit is made unsaturated at no load, then the generator size must increase ac-

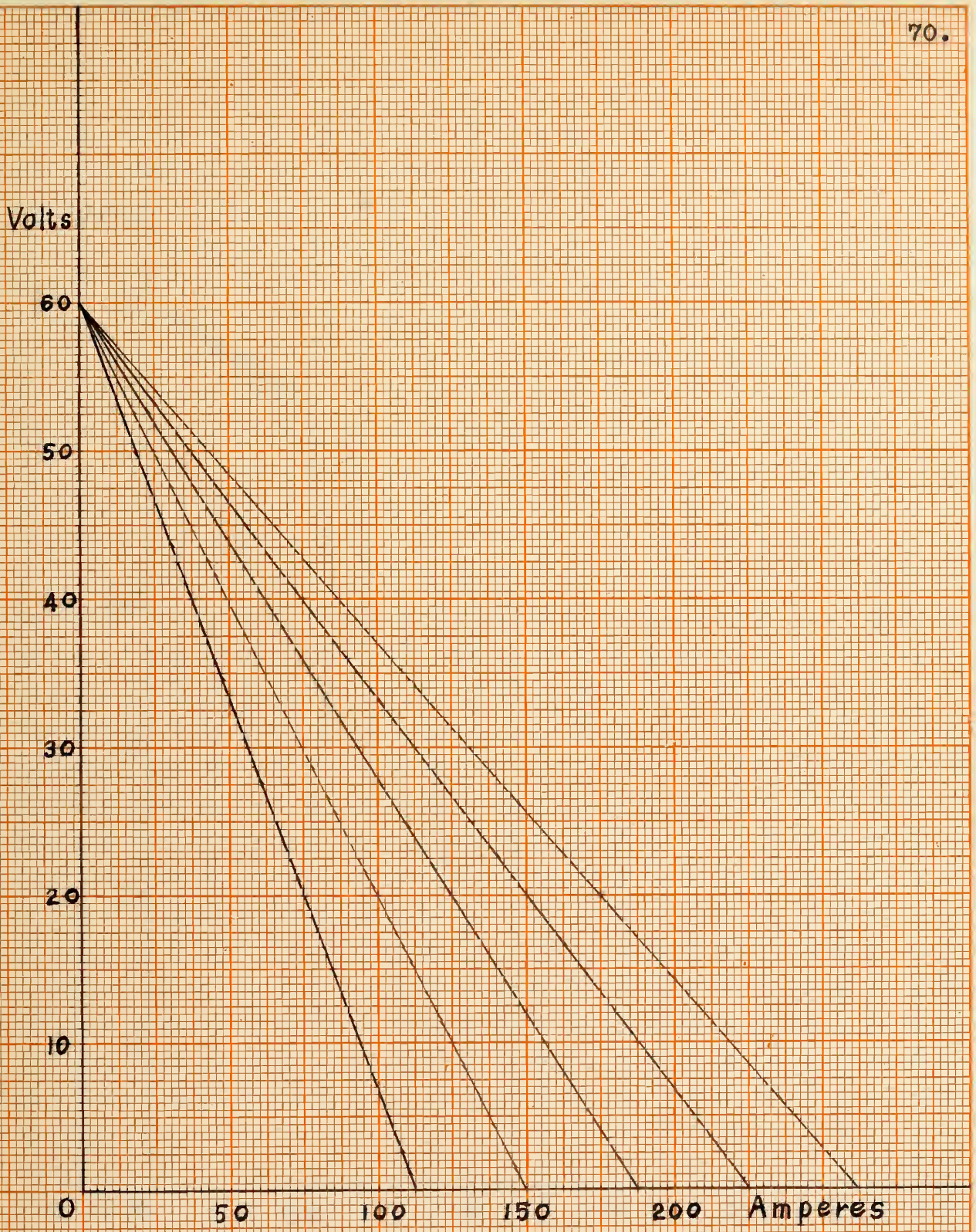

Fig. 27 - Split pole generator curves, the reversing flux pole being unsaturated - Current adjustment by means of the differential series field strength only.

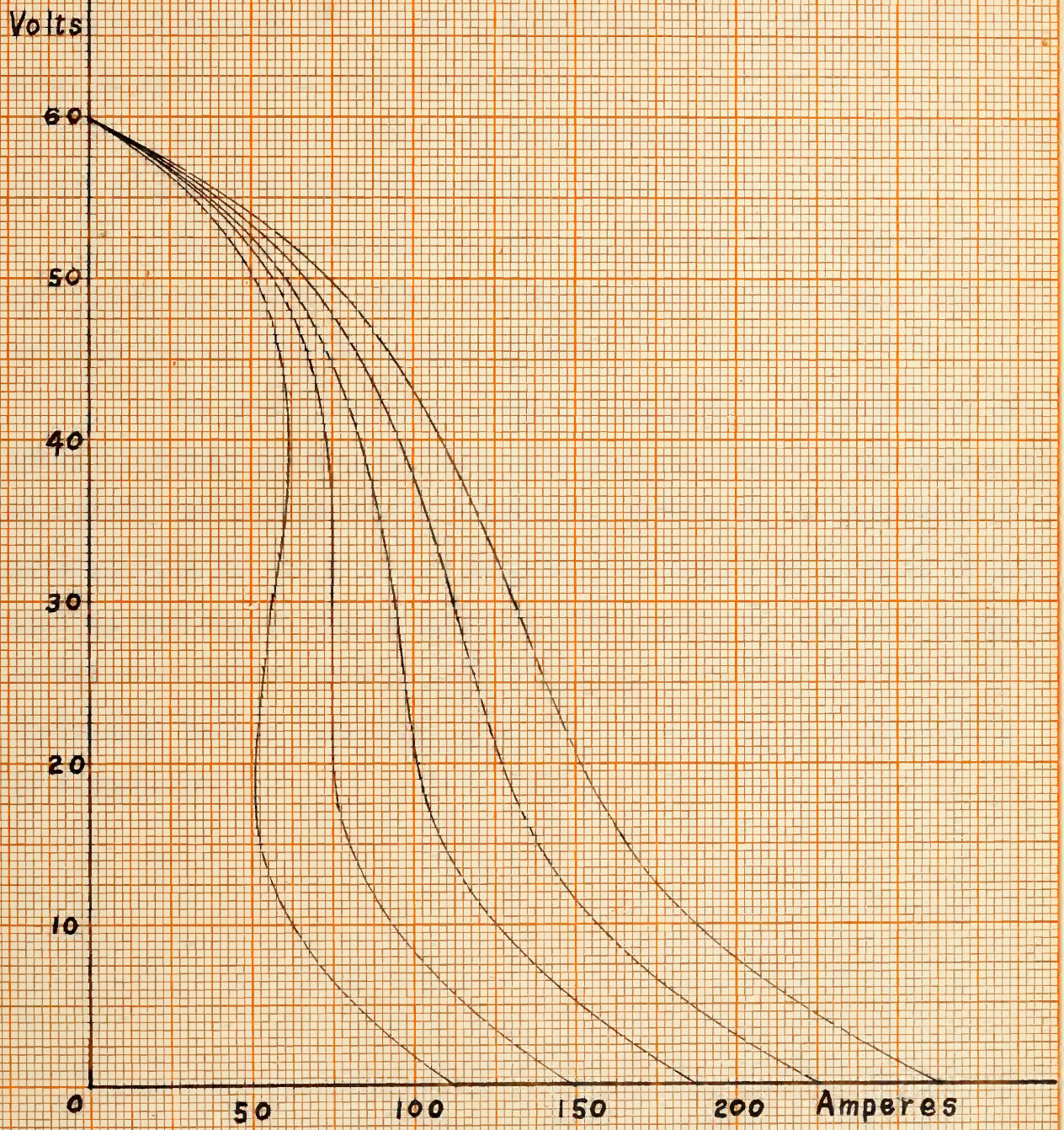

Fig. 28 - Split pole generator curves, the pole carrying reversing flux being saturated at no load and short circuit. Current adjustment by means of the differential series field strength only.

cordingly. Furthermore the welding current passes between the brushes and the commutator at only two places on the commutator instead of four. Consequently, for the same current rating a two pole armature will have a commutator approximately twice as long as will a four pole armature.

The cost of this type of generator would be high on account of its size and its special construction.

Such a generator is not very simple of assembly, for all poles are not the same, all fields are not the same, and brushes are not symmetrically placed.

For auxiliary apparatus is required a voltmeter, an ammeter, a knife switch, a field rheostat, a reactor, and means of adjusting the series field strength. This type of generator is manufactured by the General Electric Company. As a means of adjusting the series field strength they bring out taps from the series coil to the panel, and cut turns in or out by a series field dial switch, instead of using the adjustable shunt shown in Figure #26.

PART V.

CONCLUSION

28. Present Stage of Development. - Arc welding, in itself, is not a new art. It was used as early as 1881. At the time of the outbreak of the World War, arc welding was used to a very limited extent in railroad shops and factories. During the war it was largely used for the repair of old ships and the building of new ones. During the war, and since, the process has been rapidly growing in popularity, for it definitely proved its value in the shipyards. Consequently, most of the development of single operator arc welding generator has taken place in the last five years, although a few were developed before then.

Many different types of generators were produced that would weld satisfactorily. These generators, and a few other possible types, have been analyzed. A summary of the analysis is shown in Figure #29. The generators corresponding to the various numbers are as follows:

1. Separately excited generator.
2. Self excited shunt wound saturated generator.
3. Self excited shunt wound unsaturated generator.
4. Self excited addative compound wound saturated generator.
5. Self excited addative compound wound unsaturated generator.
6. Separately excited differential compound wound adjustable series generator.

7. Separately excited differential compound wound constant series generator.
8. Separately excited self excited shunt wound generator with one field adjustment.
9. Separately excited self excited shunt wound generator with two field adjustments.
10. Separately excited self excited differential compound wound generator, separate field adjustable.
11. Separately excited self excited differential compound wound generator, self excited shunt field adjustable.
12. Separately excited self excited differential compound wound generator, both shunt fields adjustable.
13. Simple separately excited differential compound wound interconnected generator.
14. Simple separately excited self excited shunt wound interconnected generator.
15. Simple separately excited self excited, differential compound wound interconnected generator.
16. First special (Westinghouse) type of separately excited self excited differential compound wound interconnected generator
17. Second special type of separately excited self excited differential compound wound interconnected generator.

18. Self excited differential compound wound third brush generator.

19. Self excited differential compound wound split pole generator.

These generators were graded with respect to their various characteristics. A is the best grade. It should be understood that though in the tabulation one type is shown better than another in regard to some special characteristic, it does not necessarily follow that a specific generator of the first type will be better than a specific generator of the second type in regard to that characteristic. This would, however, be the case if the two generators were equally well designed in all other respects. The separately excited, self excited, differential compound wound generator is rated as having a better volt-ampere curve than the separately excited differential series generator. That does not mean that if a generator of each type were taken the generator of the first type would necessarily have the best volt-ampere curve. It does, however, mean that a generator of the first type can be designed to have a better volt-ampere curve than can a generator of the second type.

Also, it should be understood that no attempt has been made to analyze every possible generator that could be used for single operator arc welding. A few of the simplest generators not in use, and the more important generators in use, were considered.

29. Probable Future Development. - Although up to the present has been a period of development, the future appears to

be a period of keen competition, with its resultant elimination of types. The generators that have the least desirable welding characteristics must go. The costly generators must go. Any generators that are unduly large, or complicated must go.

A comparison of the types as shown in Figure #29 would indicated that the separately excited differential generator with no adjustment of the series field is the most probable survivor. It is evident that all single operator generators, whether separately excited, shunt wound, or addative compound wound, that depend on resistance to reduce the voltage from 55 to 20 cannot survive, for their efficiency is too low. The self excited addative compound wound unsaturated generator probably could not compete, for its field action is too slow. The separately excited differential compound wound generator with an adjustable series will probably disappear due to the difficulty of making satisfactory provision for adjusting the series. The separately excited self excited shunt generator will probably fail because of its slow field. The self excited separately excited differential compound wound generator is probably too costly to compete. The same thing is true of all interconnected generators. The self excited differential compound wound third brush generator might fail because of sparking under the third brush. The self excited differential series split pole generator probably could not compete due to its high cost and size. It is interesting to speculate upon which types will survive, but only time will tell with certainty.

Generator #	Volt-Ampere Curve	Speed	Efficiency	Simplicity	Size	Cost	Auxiliary Apparatus
1	C	A	F	A	A	A	E
2	C	A	F	A	A	A	C
3	C	F	D	A	C	B	B
4	C	B	F	B	A	B	C
5	D	G	B	B	C	C	C
6	B	C	C	C	A	C	D
7	B	C	C	B	A	B	C
8	A	E	A	C	A	B	D
9	A	E	A	B	A	B	E
10	A	D	B	C	A	C	C
11	D	D	B	C	A	C	C
12	A	D	B	D	A	C	D
13	B	B	E	D	A	C	D
14	A	D	C	D	A	C	E
15	A	C	D	E	A	D	D
16	A	C	D	F	A	E	D
17	A	C	D	E	A	D	D
18	B	C	C	C	A	C	A
19	C	C	C	D	B	D	B

Fig. 29 - Single Operator arc welding generator comparison.

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